2004

Modeling the effects of rainfall intensity and deep chiseling on infiltration and runoff within DRAINMOD for alluvial soils

Daniel Nyabiba Moriasi
Louisiana State University and Agricultural and Mechanical College, dmoria1@lsu.edu

MODELING THE EFFECTS OF RAINFALL INTENSITY AND DEEP CHISELING ON INFILTRATION AND RUNOFF WITHIN DRAINMOD FOR ALLUVIAL SOILS

A Dissertation

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy

in

The Interdepartmental Program in Engineering Science

by
Daniel Nyabiba Moriasi
B.S., Egerton University, Kenya, 1992
M.S., Louisiana State University, 1997
December, 2004

ACKNOWLEDGEMENTS

The success of this research dissertation was due to the help from many people. All who were involved did much more than words on paper can express. Written in this acknowledgement is only a fraction of your contribution. There are also many other people whose names are not mentioned here but sees all you did and I pray that He rewards you according to his riches in glory. My sincere and deepest appreciation goes to my major Professor Dr. Richard L. Bengtson for his guidance and advice during the program period. The time you spent helping sort out my program of study and especially for recommending me for an assistantship in Engineering Science is highly appreciated. I enjoyed working with him. I would like to thank my Minor Professors Dr. George Voyiadjis and Dr. Brian Marx and the other committee members Dr. Dan Thomas and Dr. Ted Kornecki for their assistance in reviewing and editing my manuscript. I greatly appreciate the advice and guidance Dr. Marx in designing field experiments and data analysis and reporting.

I am greatly indebted to Dr. James L. Fouss, Reseach Leader for the Soil and Water Management, USDA-ARS and my supervisor and for many reasons. He provided an opportunity and a conducive environment for me to advance in my career and academics. Whenever I needed to complete a class an assignment he allowed me a flexible schedule to get school work completed in time. I am especially grateful to Dr. Fouss for requesting a one year extension of my appointment in order for me to complete my degree program. This achievement would have been impossible with out his support and constructive criticism and technical guidance. I would like to thank Dr. Brandon Grigg for advice with field experiments. I am grateful to Dr. Wayne Skaggs, Professor in

Biological and Agricultural Engineering, NCSU and his research associate Dr. Glen Fernandez for technical advice on the changes made in DRAINMOD. Special thanks to Dr. Steven Hall for his guidance, invaluable advice, encouragement and prayers throughout my research period. Also very special thanks Mr. Frank Canfield (Pops) for a thorough and excellent editing of my dissertation. I am grateful to Mr. Kelvin Lewis for assistance with field experiments. Special thanks go to Mr. Gary Foster for his great assistant in the setting up the laboratory for the of soil core samples. I am grateful to my colleague Becky for your great suggestions and great ideas that were useful and for help with table and room setup during my dissertation defense. The cake you, Mike and Pops made was great. God bless you all. Many other people have contribution in many other ways.

I will always be thankful to Dr. Larry Gaultney for your encouragement, support, advice and prayers. God literally used Dr. Larry D. Gaultney to get me to graduate school. There are no enough words to tell all you and your family did for me. You are and will always be a role model to me. International Christian Fellowship (ICF) and Istrouma Baptist Church Sunday school brothers and sisters in Christ have been such a support for me. They have prayed for me, encouraged me and have been there any time I have needed them. These have been angels sent by God to help me stand through this period. God especially blessed me with Simon and his family. His little boy, Timothy has been such a joy and brought back a smile even a long night of working and obtaining no results. I thank Simon for all the help, support and prayers. For Mueni, Cate and I don’t have enough words to express what a blessing she has been to us. She is a strong woman of God, an encourager, and a joy to be around. She has taken care of Cate and I, taken care of the food, the laundry and has lifted a burden of things I should have worried about. The list is endless we cannot thank her enough.

To my love, my beautiful jewel, my wife Cate, thank you for your understanding during my moments of weakness, frustration, anger, tiredness, joyfulness, success, ……, and …..As the saying goes, behind every successful man is a woman, I can say is I could never have done this without her love, support and challenge. You are indeed a special woman and one of a kind. Your dedication to excellence in you do, inspired me to work harder. Cate has completed her Ph.D. program in a record time while, working on her Masters degree in Agricultural Economics and while carrying our baby! I am so grateful to God for bringing her into my life.

I am very grateful to my mother who raised me and instilled values in me and taught me the fear of God. I am grateful for my brother Simon and sister in-law Emily, for all their support throughout my school life, my brother Zachariah for the part you played to my coming to the US and all my brothers and sisters. I am grateful for Mummy and Daddy for your great love for Cate and I. Daddy, your dedication to work is a great inspiration and challenge to us. Thank you Jackie and Kizito for thinking about us, I wish you guys God's blessings.

All in all I have been blessed of God. God has been so good to me and has brought me from far and has provided all that I have needed to walk this journey. I praise my God, the father of my Lord Jesus Christ for showing me favor and I will live to glorify Him and sing of His mercy and faithfulness for He has been a good God.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

[ξ] A possible reason for under-prediction by DRAINMOD-K_s-STMAX was leveling/grading done in Feb.

ABSTRACT

Accurate hydrologic models are needed to aid engineers and researchers design, install and evaluate efficient and cost-effective agricultural water management systems to reduce risks associated with food production, and to reduce soil erosion and water pollution. One model used for the alluvial soils of Louisiana is DRAINMOD. This model does not accurately predict infiltration and runoff for the crusting-prone alluvial soils of Louisiana. The main goal of this study was to modify the current DRAINMOD model to incorporate the effects of rainfall intensity and deep chiseling to improve its estimation of infiltration and surface runoff. The second goal was to use information gained from the modified DRAINMOD model to assess how long farmers and environmentalists benefit from a particular deep chiseling operation and determine optimum deep chiseling frequency for given climatic conditions.

A methodology for using a five-minute rainfall time increment subroutine within DRAINMOD was developed. Field experiments yielded an initial vertical saturated hydraulic conductivity of 2.0 cm/hr, a final vertical saturated hydraulic conductivity of 0.50 cm/hr and exponent of 0.03 cm^{-1} for model calibration. Deep chiseling modifications resulted in the DRAINMOD-STMAX, DRAINMOD-K_s and the combined DRAINMOD-K_s-STMAX models. DRAINMOD-STMAX, DRAINMOD-K_s and DRAINMOD-K_s-STMAX model improved surface runoff prediction by 57%, 73%, and 82% respectively in1995/96 season and by 27%, 45%, and 62% respectively in 1996/7 season.

Using DRAINMOD-K_s-STMAX model, deep chiseling a Commerce silt loam soil increased infiltration by 9.4% and reduced runoff by 19.7% in 1995/96 season and by

5.7% and 19.2% respectively in 1996/97 season. All benefits resulting from deep chiseling were lost after 115 cm of rainfall since deep chiseling. Farmers should deep chisel once every year when annual rainfall is greater than 100 cm and once every two to three years when annual rainfall is less than 100 cm. Sixty percent or more of the maximum deep chiseling benefits had been lost by planting time; therefore, farmers need to deep chisel their fields just before planting.

Further work is needed in the field to determine other factors affecting variation of K_s, to validate the DRAINMOD-STMAX, DRAINMOD-K_s and DRAINMOD-K_s-STMAX models, and to incorporate rainfall intensity subroutine.

CHAPTER ONE

GENERAL INTRODUCTION

1.1.Background of the Importance of Modeling the Effects of Rainfall Intensity and Deep Chiseling within DRAINMOD Simulation Model for Alluvial Soils

Exposure of fine textured alluvial soils, deposited by floodwaters over thousands of years in Louisiana, to high amounts of rainfall leads to the formation of a soil surface seal, which upon drying form a continuous sheet (crust) on the soil surface (Martinez-Gamino, 1994). Soil surface seal is formed when high intensity rainfall consisting of high-energy raindrops falling on the surface of fine textured soils such as alluvial soils, rapidly breaks down the soil aggregates into fine particles that seal the soil surface pore spaces (Haan et al., 1994). Soil surface seal formation coupled with machine traffic, during field operations, reduces water infiltration and increases surface runoff (Hillel, 1982). Low water infiltration and high runoff may result in less water and crop nutrients available within the crop root zone leading to lower crop yields and increased water pollution into the surrounding water streams, which may pose a serious danger to aquatic life in the surface runoff destination waters. This is a great concern to aquatic and crop farmers in Louisiana who depend on agriculture for their livelihood. Agriculture is highly significant to Louisiana's economy, contributing approximately $ 9 billion to Louisiana's economy in 2003 [75 percent of which was contributed by crops, aquaculture, and freshwater and marine fisheries] (LSU Agcenter, 2004). Consequently, aquatic and crop farmers and environmentalists need information and advice on cost-effective best management practices (BMPs) that will increase crop yields by increasing the flow of water and crop nutrients into the crop root zone while reducing water pollution.

The challenge for engineers and researchers has been and still is to design, install and evaluate efficient and cost-effective agricultural water management systems in order to reduce risks associated with food production, and to reduce soil erosion and water pollution. The design of optimum agricultural water management systems requires data for different possible designs depending on the climatic conditions for a given soil type and field situation.

One tool that has been used by engineers and researchers to generate the needed data is modeling. Modeling can save time and money because it provides the ability to quickly and efficiently analyze or simulate possible multiple design scenarios over long periods and compare results to determine the best design for particular soil field and climatic conditions. The success of any model to aid engineers and researchers in their efforts to design optimum agricultural water management systems depends to a large extent on its ability to accurately estimate the components or elements being evaluated.

Engineers continue to develop new and more accurate models (Skaggs, 1978; Beasley et al., 1981; Ward et al., 1988) or they continue to refine the current models (Bengtson et al., 1985; Fouss, 1985; Fouss et al., 1989; Morari and Knisel, 1997; Dillaha et al., 1998; Im et al., 2000) to give better component predictions. One such model that has been developed (Skaggs, 1978), modified (Bengtson et al., 1985; Fouss, 1985; Fouss et al., 1989), and used (Gayle and Skaggs, 1978; Fouss et al., 1987; Wright et al., 1992; Saleh et al., 1994) for the alluvial soils of Louisiana is DRAINMOD.

DRAINMOD is a computer model that was developed at North Carolina State University in the late 1970s (Skaggs, 1978). This model is based on the water balance in the soil profile and uses long-term (20 to 40 years) climatological records to simulate the performance of drainage and water table control systems on a continuous basis. DRAINMOD predicts surface runoff, water table depth, drainage outflow, soil water content, evapotranspiration (ET) and infiltration on hourly, daily, monthly or an annual basis in response to given soil properties, crop variables, climatological data, and site parameter inputs. However, DRAINMOD does not accurately predict infiltration and runoff for the crusting prone alluvial soils of Louisiana. The following are some of the possible reasons for this inaccurate prediction by DRAINMOD: (1) The use of hourly rainfall time increments (2) Assumption of constant Green-Ampt parameters and hence constant vertical saturated hydraulic conductivity (K_s) and (3) Assumption that maximum surface depressional storage (STMAX) is constant irrespective of tillage operations.

1.1.1 Hourly Rainfall Data Time Increments- Rainfall Intensity Effect

DRAINMOD uses hourly rainfall because hourly rainfall data was readily available in many locations in the United States at the time of its development (Skaggs, 1978). The rainfall distribution within the hour is assumed to be uniform, which may not give a complete description of the within hour variation in rainfall. Short time increments for the rainfall input data would be expected to give better predictions of model components than less frequent data. Shorter rainfall time increments are easily available now because of the increased use of data loggers at weather stations throughout the United States. Hourly rainfall rates may not be a problem when estimating infiltration and runoff by the current DRAINMOD model for areas where the amount of precipitation is low and the rainfall distribution is relatively uniform. Hourly rainfall rates may result in inaccurate prediction of infiltration and runoff in the southeastern United States where rainfall amounts are significant (Bengtson and Carter, 2004) and where all rainfall in a given event may fall within minutes (LSU AgCenter Climate, 2004).

For instance, the annual precipitation average for Louisiana is approximately 1550 mm (Bengtson and Carter, 2004) and the distribution of rainfall within any particular hour appears to be random and is rarely uniform. In such a case if the amount of rain is significantly high during only five minutes and an hourly rainfall rate is used in the model, it may lead to overestimating infiltration while underestimating surface runoff. For example, 30 mm of rain falls in a given hour on a soil that has a maximum water infiltration rate (infiltration capacity) of 30 mm/hr and a maximum soil surface depressional depth of 1 mm. If the rainfall is uniformly distributed, which is the assumption made by the current DRAINMOD model, 0.5 mm of rain would fall every minute for a rainfall rate of 30 mm/hr, which is equivalent to the infiltration capacity. Therefore, the current DRAINMOD model would predict that all the water would infiltrate through the soil surface into the subsoil. On the other hand, if all the 30 mm falls within ten (10) minutes during this hour, the rainfall rate is 180 mm/hr and not 30 mm/hr assumed by DRAINMOD. In a case like this, where the rainfall rate is higher than the infiltration capacity, only 5 mm would infiltrate during the ten-minute period. Of the remaining rainfall water (25 mm), about 1 mm would be expected to fill the soil surface depressions of which part would infiltrate and part would evaporate, and the remaining (24 mm) would run off the soil surface. If the hourly rainfall rate is assumed as in the current DRAINMOD, infiltration would be overestimated by at least 24 mm and soil surface runoff underestimated by a similar amount.

1.1.2 Problem of Constant K_s and STMAX – Deep Chiseling Effects

The short duration and high intensity rainfall on alluvial soils in southeastern United States also leads to soil surface seal formation (Martinez-Gamino, 1994) especially during seedbed preparation and planting periods when the soil is bare. Machine traffic and compaction tend to accelerate the sealing/crusting problem. On one hand, the formed surface seal leads to low infiltration and high surface runoff, both of which are undesirable. On the other hand the surface seal may lead to inaccurate prediction of infiltration rates and hence infiltration and runoff by DRAINMOD. The Green and Ampt equation, which is used to predict infiltration rates in DRAINMOD, gives good results for soils with uniform soil profiles, soil profiles that become denser with depth and soils with partially sealed surfaces (Skaggs, 1978). In other words, the Green and Ampt equation gives good results for soil profiles having the same hydraulic properties throughout the profile, or soil profiles where the hydraulic properties decrease with depth or for soils that have limited surface sealing effects. This is not the case with alluvial soils. For instance, for the Commerce silt loam soil [fine silty, mixed, non-acid, thermic Aeric Flivaquent], a southern Louisiana alluvial soil, the top (surface) soil layer is the least conductive (Rogers et al., 1991) due to the formation of soil surface seal (Martinez-Gamino, 1994). Saturated hydraulic conductivity for the Commerce silt loam soil increases with depth from 1.46 cm/hr (0.6 m) to 4.39 cm/hr (1.5 m) and then decreases with depth to 2.88 cm/hr (2.4 m) as determined by Rogers et al. (1991). A tillage practice that has been used in Louisiana to break the soil surface crust and the hard pan in order to increase infiltration and reduce surface runoff is deep chiseling (Bengtson et al, 1995).

To deep chisel a field, a farmer attaches short, angled subsoil shanks to a tractor tool bar and pulls them through the soil, breaking the soil to at least 30cm below the ground surface (Grigg and Fouss, 2002). Deep chiseling increases infiltration and reduces surface runoff by increasing the vertical component of saturated hydraulic conductivity (K_s) of the top layer of soil and increasing the maximum surface depressional storage (STMAX). Soil saturated hydraulic conductivity is a measure of the soil's ability to transmit water under saturated conditions. Maximum surface depressional storage is related to the depth of the soil surface depressions and ability of the soil surface to hold/pond water. Roughly, tilled fields hold considerable amounts of water in the surface depressions thus reducing surface runoff as opposed to smooth surface fields, which lead to high surface runoff. Some of the ponded water held in the surface depressional storage infiltrates into the subsoil and some evaporates into the atmosphere.

Unfortunately, the benefits of deep chiseling are only temporary because the soil surface seal reforms and soil compaction increases gradually to the previous condition as the fine particles fill the soil pore spaces and surface depressions are smoothed out after subsequent rainfall events. The above conditions will decrease K_s and STMAX.

Although K_s and STMAX decrease gradually depending on total rainfall (Freebairn et al., 1991) over time [cumulative rainfall since deep chiseling], the current DRAINMOD model assumes both K_s and STMAX remain constant irrespective of any tillage practice carried out (Skaggs, 1978). Therefore, the current DRAINMOD model is likely to give less accurate predictions of both infiltration and runoff depending on the stage of surface seal reformation, which is a function of cumulative rainfall since the deep chiseling operation. As a result, the current DRAINMOD model cannot be used to quantify how long farmers and environmentalists may benefit from a particular deep chiseling operation and how frequently to deep chisel a farm field, both of which depend on the climatic factors such as cumulative rainfall since deep chiseling.

1.2. Goals of the Study

The main goal of this study was to address three problems (1) the use of hourly rainfall data (2) assumption of constant K_s and (3) assumption of constant STMAX. This was done by modifying the current DRAINMOD model by incorporating the effects of rainfall intensity and deep chiseling to improve its estimation or prediction of infiltration and surface runoff. The information gained from long-term modified DRAINMOD simulations for different climatic conditions will aid engineers in the design, installation and evaluation of efficient and cost-effective agricultural water management systems. The second goal was to use information gained from the computer simulations to assess how long farmers and environmentalists benefit from a particular deep chiseling operation and thereby determine optimum deep chiseling frequency for given climatic conditions.

1.3 Specific Research Objectives

1. To modify DRAINMOD by writing and incorporating a five-minute infiltration calculation subroutine, which uses five (5) minute rainfall rates if hourly rainfall is equal to or more than 2mm, thereby modeling the effect of rainfall intensity within DRAINMOD.
2. To carry out field measurements of vertical surface saturated hydraulic conductivity (K_s) at different stages of surface soil seal reformation on alluvial soils of Louisiana

depending on cumulative rainfall after deep chiseling to be used in calibrating a dynamic K_s mathematical model after a deep chiseling operation.

3. To write and incorporate into DRAINMOD a dynamic K_s subroutine, by developing a theoretical/mathematical equation, using the measured K_s field data after deep chiseling to calibrate the mathematical K_s equation and coding the mathematical equation within DRAINMOD.
4. To write and incorporate into DRAINMOD a dynamic STMAX subroutine, by developing a theoretical/mathematical equation as soil surface depressions smooth out over time, using Gayle and Skaggs' (1978) data, modified for a deep chiseling operation, to calibrate the mathematical STMAX equation and coding the mathematical equation within DRAINMOD.
5. To validate the DRAINMOD modifications (1,3,and 4) by comparing estimated runoff with measured field runoff data from USDA-ARS Ben Hur Research site fields, located in Baton Rouge, Louisiana and to estimate and compare infiltration and runoff using the modified and original DRAINMOD for the same period.

CHAPTER TWO

LITERATURE REVIEW

2.1 Alluvial Soils

2.1.1 Formation and Location of Alluvial Soils

Alluvial soils, deposited by floodwaters over thousands of years, cover the Red River valley, Mississippi Alluvial Plain and other stream valleys along the Mississippi River. These soils cover the whole region of the Lower Mississippi River Valley (LMRV), which goes through Illinois, Mississippi, Louisiana, Arkansas, Tennessee, Kentucky, Alabama, and northeast Texas (Anonymous, 2002). Alluvial soils are made up of different soil types depending on the parent material and the source.

2.1.2. Composition of Alluvial Soils

According to Lindbo et al. (2000), Grenada [fine-silty, mixed, thermic Glossic Fragiudalf] soils are common in the uplands of the LMRV and are distinguished by a fragipan within 100 cm of the surface and are overlain by a ≥ 5cm thick glossic horizon in which the fragipan is degraded. Fragipans are characterized as subsurface horizons that are naturally occurring, dense, brittle when moist, root restrictive, and slowly or very slowly permeable (Soil Survey Staff, 1992) which leads to low infiltration rates. On the other hand on the deltaic surfaces of the LMRV, there are fourteen (14) most widely occurring soil types with average horizon A clay content [calculated from Worsham and Sturgis (1941) samples data] ranging from 8.0 % for Portland si. l. to 55% for Sharkey clay [very fine, montmorillonitic, nonacid, thermic Vertic Haplaquepts]. Other alluvial soils in the LMRV include Tunica clay [clayey over loamy, montmorillonitic, nonacid, thermic Vertic Haplaquept] (Heatherly et al., 1990), Norwood silt loam [fine-silty, mixed (calcareous) thermic Typic Udifluvent] (Moore, 1998), Entisols, Inceptisols and Alfisols (Aslan and Autin, 1998) and Commerce silt loam [Aeric Fluvaquent, fine-silty, mixed, nonacid, thermic] (Southwick et al., 2003). These soils, coupled with the use of fertilizers and proper farming methods, are very productive with high potential crop yields.

2.1.3. Crop Production Potential and Economic Importance of Alluvial Soils to Louisiana

Farmland occupies 3.3 million hectares, which is 30 percent of the total area of Louisiana, of which 65 percent is used to raise crops (LSU AgCenter, 2004). Therefore, agriculture is highly significant to Louisiana's economy, contributing approximately $ 9 billion to Louisiana's economy in 2003 (LSU Agcenter, 2004). According to the LSU Agcenter (2004), the total farm value of all plant enterprises in 2003 was $2.614 billion and the value added was $3.413 billion for a total value of all crop enterprises to the Louisiana economy of $6.027 billion [67% of agricultural contribution to the economy]. Besides the types of alluvial soils and crop inputs such as fertilizers and pesticides, crop yields are very much dependent on the amount, duration, and distribution of rainfall during the crop growing season.

2.2 Rainfall Patterns in Louisiana

2.2.1.Rainfall

The primary source of water for agricultural production, for many parts of the world is rainfall or precipitation. Rainfall is characterized by its amount, intensity and distribution in time.

The amount of rainfall is the depth of water (in mm) received during a rain event. Suppose that during one hour, a certain area receives a total amount of rainfall water of 20 mm (20 mm/hr). Further suppose this rainwater falls during two short (10 minute) showers of 10 mm each at the beginning and the other at the end of the hour, the rainfall is poorly distributed over one hour. On the other hand, if the rainwater is supplied continuously and evenly during the hour, the rainfall water is uniformly distributed. Rainfall intensity is the depth of water (in mm) received during a shower divided by the duration of the shower (usually in hours); for a given amount of rainfall the shorter the shower duration the higher the rainfall intensity.

2.2.2. Rainfall Patterns in Louisiana

Precipitation is high in Louisiana, with annual precipitation often exceeding 1500 mm and monthly rainfall frequently exceeds 250 mm (Fouss, et al., 1987). Occasionally annual precipitation exceeds 2000 mm in this area (Bengtson and Carter, 2004). Too much water is undesirable because it can lead to a rise of the groundwater table and undesirable saturation of the root zone if there is insufficient drainage. The amount of precipitation in Louisiana is not always high but in some years it may be low during dry years. Too little water during the growing season causes plants to wilt resulting in loss of crop yield or even crop failure where there is no irrigation.

The distribution of rainfall in Louisiana varies from year to year, season to season, month to month, day to day, hour to hour and within the hour (LSU AgCenter Climate, 2004). According to Bengtson and Carter (2004) the average annual rainfall for the period 1988 to 2000 in Baton Rouge Louisiana was 1550 mm, with annual rainfall ranging from a high of 1997 mm in 1992 to a low of 998 mm in 2000. Seasonal rainfall differences in Louisiana and other southeastern United States along the Gulf Coast are caused by a variety of sources, which are partially dependent on season (Keim and Faiers, 1996). There are three rain event types; Frontal, Gulf Tropical Disturbance and Airmass

(Keim and Faiers, 1996). Frontal events occur when rainfall is produced just before, during, or just after the passage of a frontal boundary. Gulf Tropical Disturbance events are those events generated by tropical systems ranging from weak easterly waves to hurricanes. Finally, airmass events are those events that show no surface manifestation of a front or a tropical disturbance for example convective storms.

According to Keim and Faiers (1996) heavy events in winter and spring are generated by frontal weather systems, while tropical disturbances and airmass (free-convective) storms mainly produce summer and fall events. Generally, a frontal storm generates longer periods of rain with low rainfall intensities in contrast to convective rainfall, which is characterized by short storm duration with fairly high rainfall intensities. However, due to high amounts of rainfall in the southeastern United States (Bengtson and Carter, 2004), the rainfall intensities are generally high even with long duration storms in the winter and spring seasons.

High intensity rainfall is less useful to crops when compared to low intensity rainfall because most of the rainwater runs off the ground surface and does not infiltrate into the root zone for crop use. In addition high intensity rainfall usually has high-energy raindrops that fall on the soil surface. In fine textured soils, like alluvial soils, the soil aggregates rapidly break down into fine particles that seal the soil surface especially during seedbed preparation (Haan et al., 1994).

2.3 Soil Surface Seal Formation

Alluvial soils of southeastern United States are often subjected to high amount and intensity rainfall. The impact of high-energy raindrops breaks up the surface soil clumps into fine aggregates, which fill the soil pores and form a surface seal (Haan et al.,

1994) especially during seedbed preparation when soils are bare. The soil surface seal is compacted by further raindrops. Upon drying, the cementing agents in clays form and bind soil particles together forming a continuous sheet (crust) on the soil surface (Martinez-Gamino, 1994). The main cementing agents in soils are silica in semiarid zones, sesquioxides in subtropical zones, and organic matter in both cases (Martinez-Gamino, 1994). Other cementing agents include amorphous silicate (SiO_2), and Si-Fe complexes (Chartres et al., 1990). Soil surface seal formation leads to lower soil water infiltration and increased soil surface runoff, both of which have a negative effect on crop yields and water pollution.

2.4 Increased Soil Surface Runoff and Its Implications on Crop Yields and Pollution in Louisiana

The volume of surface runoff is related to the soil surface conditions, duration and amount of rainfall. The formation of soil surface seal on alluvial soils in Louisiana leads to lower soil water infiltration and high surface runoff (Martinez-Gamino, 1994). On the other hand large rainfall amounts in Louisiana (Bengtson and Carter, 2004), which is usually associated with long storm duration although quite often "it can rain like cats and dogs for only a short time", also leads to high soil surface runoff volume. High runoff leads to lower crop yields because of the loss of crop nutrients such as nitrogen, phosphorus and potassium. Loss of crop nutrients (Bengtson et al., 1998; Willis et al, 1998) and pesticides (Bengtson et al., 1989; Southwick et al., 2003) also leads to water pollution, which could pose a great danger to aquatic animals if it exceeds allowable water quality standards.

Worldwide annual agricultural runoff contributed an estimated 4.65 million tons of nitrogen (N) to off-farm aquatic ecosystems, primarily in the form of nitrate (NO_3^-)

(Duttweiler and Nicholson, 1983). Using historical data, Goolsby et al. (2000) showed that concentration of nitrate in the Mississippi River and some of its tributaries have increased by 2 to more than 5 times since the early 1900s with the principal source being basins that drain agricultural fields along the Mississippi River. Nitrogen from croplands can lead to oxygen-depleted water in the runoff destination waters, which may endanger the aquatic life. For example in the summer of 1999, billions of creatures suffocated in the northern Gulf of Mexico, starting in the spring [right after the application of fertilizers and herbicides] when waters were gradually depleted of life-giving oxygen [hypoxia] (Ferber, 2001). Therefore, water runoff from pollution is a great concern to aquatic organisms and those who depend on those organisms for survival and their livelihood.

The total farm value of all fish and wildlife enterprises in Louisiana was $446.5 million for 2003 and the value added was $327.4 million for a total value of all fishery and wildlife enterprises to Louisiana economy was $773.9 million (approximately 9% of the total agricultural contribution) (LSU Agcenter, 2004). Of the total farm value of all fish and wildlife enterprises, 88% was contributed by the combination of aquaculture, freshwater fisheries, and marine fisheries.

In addition to economic losses for farmers engaged in aquaculture caused by high levels of nutrient concentrations in surface runoff, pesticides may cause contamination to the fish (Dowd et al., 1985), which could pose serious health risks to humans. Also, if the nitrates (> 10ppm nitrate-N) in the surface runoff end in drinking water streams and wells, it can lead to health problems in humans. In human blood NO_3^- is reduced to NO_2^- and reacts to reduce the capacity of red blood cells to carry oxygen and causes a blood disorder known as methemoglobinaemia or blue baby syndrome (Bruninng-Fann and

Kaneene, 1993). Therefore, it is desirable to adopt farming practices that will reduce surface runoff during wet years by increasing soil water infiltration in addition to using the necessary amount of fertilizers for crop growth to avoid ground water contamination due to leaching.

2.5 Infiltration

The ability to calculate crop water budgets, pesticide and fertilizer runoff, infiltration of fertilizers and chemicals depends on the ability to quantify infiltration. Therefore the knowledge of the infiltration process is necessary if water and dissolved crop nutrients or fertilizers are to be made available to crops especially during dry years and if solutions to surface runoff problems during wet years are to be found.

Infiltration is defined as the process by which water passes through the soil surface and enters into the subsoil. The soil functions as a pervious medium that provides channels for water to move through the surface. The rate of water passage into subsoil is called the infiltration rate and it varies in time during any single rainfall event, typically decreasing significantly as the soil gets wet. If a rain event continues long enough the infiltration rate becomes constant, that is it reaches a steady state. Infiltration capacity or infiltrability refers to the infiltration rate if water is freely available at the soil surface, in other words under a ponded soil surface.

2.5.1 Phenomena of Water Infiltration in Unsaturated Zone

Hillel (1982) gives a description of moisture distribution in the soil profile during infiltration as shown in Figure 2-1 below. For a homogeneous soil profile at any moment during infiltration under ponding, the surface of the soil is saturated, maybe to a depth of several millimeters or centimeters. Beneath this zone is a less than saturated zone called the transmission zone, followed by a wetting zone, in which soil wetness decreases with depth at a steepening gradient down to a wetting front. At the wetting front the moisture gradient is so steep that there appears to be a sharp boundary between the moistened soil above and the relatively dry soil beneath (Hillel 1982).

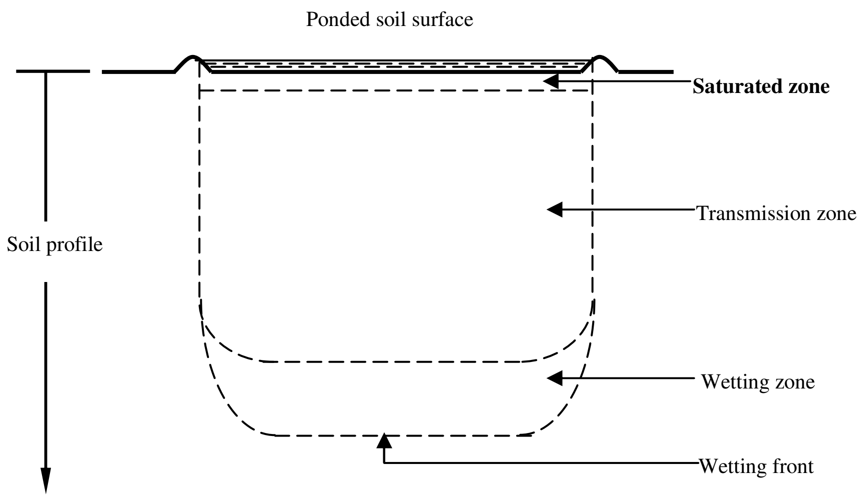


Figure 2-1. The infiltration moisture profile (after Hillel, 1982)

2.5.2 Infiltration Scenarios

There are three scenarios of infiltration during a rain event. If rainfall intensity (rainfall rate) is less than the infiltration rate, all the water that reaches a soil surface infiltrates into the subsoil. On the other hand, if the rainfall intensity is greater than the infiltration capacity, the extra water fills the soil surface depressions. If ground is sloping, depression storage may be small, and surface runoff begins soon after depression storage is filled. If the whole soil profile is already saturated, water fills the depression immediately if the rainfall intensity exceeds the infiltration capacity.

2.5.3 Factors Affecting Infiltration

Generally, infiltration rate depends on the soil, plant, climatic (Skaggs, 1980), and management factors. Soil factors affecting infiltration rate are antecedent soil moisture content, soil texture, soil aggregation and structure, soil pores, soil surface conditions (crust and compaction), and the presence of impeding layers within the soil profile.

A wet soil has a lower infiltration rate than a dry one (Haan et al., 1994), attributed to the fact that some of the colloids in the wet soil swell reducing both the pore space and the rate of water movement within the soil (Schwab et al., 1993). In general course-textured gravels and sands have higher infiltration rates than do fine-textured clays. According to Hillel (1980), the steady infiltration rates [under saturated conditions and equivalent to saturated hydraulic conductivity] for different soil types are as follows. Gravels and sands > 20 mm/hr, sandy and silty soils 10-20 mm/hr, loams 5-10 mm/hr and clay soils 1-5 mm/hr. D'Andrea (2001) also reported that soil hydraulic conductivity of clean sandy gravel might be ten or more orders of magnitude higher than that of plastic clay, pretty much in agreement with Hillel's (1980) results.

Soils that have stable and strong aggregates with granular or blocky soil structure have higher infiltration than soils that have weak, massive, or platelike structure. Generally soils that have a smaller structural size such as sands have higher infiltration rates than soils with that have a large structural size. A soil surface with a highly porous structure has a greater initial infiltration rate than that of a uniformly structured soil. In contrast, a compacted soil surface and a profile covered by a surface crust of lower conductivity leads to a lower infiltration rate than that of the uniform [not compacted] soil (Hillel, 1982).

Plant factors that affect infiltration include canopy cover, and depth of the root zone (Skaggs, 1980). Plant canopies intercept the energy of raindrops, thereby minimizing their impact on the soil surface. For this reason, there is high infiltration and low runoff on a soil with a full and established canopy compared to low infiltration and high runoff on a bare soil (Haan et al., 1994).

The climatic factors that affect infiltration are intensity, duration, and time distribution of rainfall, total rainfall, temperature and whether or not the soil is frozen (Skaggs, 1980). If rainfall intensity is greater than the infiltration rate, water will accumulate on the surface until impoundment areas are full, and then runoff will occur. High intensity rainfall also leads to soil surface seal formation, which has low infiltration whereas low intensity rainfall does not cause surface sealing. On the other hand short duration rainfall is associated with high rainfall intensity, which leads to surface sealing and low infiltration. The longer the rainfall duration the lower the infiltration rate because a wet soil swells reducing both the pore space and the rate of water movement within the soil (Schwab et al., 1993). Finally, a frozen soil surface greatly slows or completely stops infiltration (USDA, 1998) because pores are blocked by ice. This is especially of concern if freezing weather is followed by snowmelt and/or rain in which case most of the water is lost through runoff.

Alluvial clay soils of Louisiana are often subjected to high amount and intensity rainfall. The impact of high-energy raindrops, during seedbed preparation and planting periods, breaks up the surface soil clumps into fine aggregates, which fill the soil pores and form a surface seal (Haan et al., 1994). The soil surface seal is compacted by further raindrops. Upon drying, the cementing agents in clays form and bind soil particles together forming a continuous sheet (crust) on the soil surface (Martinez-Gamino, 1994). However, if good farm management practices are used, infiltration on surface seal formation prone soils can be increased.

There are three management practices that have been used to increase infiltration by improving soil structural stability on surface seal formation prone soils. These include organic in the soil or on the soil surface (crop residues or organic amendments), biological (crops or trees), and tillage based systems (Rao, 2004). Addition of organic amendments such as farmyard manure, organic polymers (Levy et al., 1992; Shainberg et al., 1992) and crop residues increase rainfall infiltration rates either by protecting the surface from rain drop impact [crop residues] or by improving the soil structural and aggregate stability [farmyard manure and organic polymers such as polyacrylamide (PAM)] (Gicheru et al, 2004; Rao, 2004). On the other hand, biological systems protect the soil surface by providing a canopy cover for extended periods and they improve soil structure through the activity of roots and addition of litter (Rao, 2004).

Tillage is the most commonly used management practice to break the surface soil seal and restore reasonably high infiltration rates to reduce runoff and improve crop yields (Rao, 2004). Some of the tillage practices that have been used to break the surface seal to improve infiltration depending on the soil type and the cropping system are plow-till (van Es et al., 1999), conservation tillage (Barisas et al., 1978), in-row sub soiling (Cassel et al., 1995), shallow [10 cm deep] and deep [20 cm deep] tillage (Rao et al., 1998), deep chiseling [up to 30 cm depth], subsoiling (35 to 45 cm deep) (Pearce et al., 1999) and chisel-plow (Ankey et al., 1995).

van Es et al. (1999) found that plow till increased infiltrability for clay loam and silt loam soils in New York and silt loam and sandy loam soils in Maryland. Their finding is in line with Barisas et al. (1978) who reported that conservation tillage practices reduced the total nutrient loss by controlling erosion due to increased infiltration rates. Ankey et al. (1995) found that chisel plow tillage increased ponded infiltration rates by 31 and 56 % respectively for trafficked and untrafficked interrows of soils in Minnesota and Nebraska. One of the tillage practices that have been used in Louisiana to break the surface seal on alluvial soils and reduce runoff and improve yields is deep chiseling (Bengtson et al., 1995). Deep chiseling used to be a common practice in the Lower Mississippi River Valley. In more recent years farmers have not used it because they did not see any economic benefits and because minimum tillage was adopted which required less energy for the equipment (Grigg and Fouss, 2002). But deep chiseling is still needed in this region when subsurface drainage is used.

In previous research (Bengtson et al., 1995) when deep chiseling was carried out every one year to two years [and data collection beginning right after deep chiseling] subsurface drainage systems decreased runoff. However, research by Grigg et al. (2003) from 1995 to 1996 on fields with subsurface drainage, whose measurements were taken 3 to 5 months after deep chiseling, showed that subsurface drainage did not reduce surface runoff. Grigg et al. (2003) took measurements 3 to 5 months after deep chiseling the soil because their research objectives at the time did not include determination of the effect of deep chiseling.

Deep chiseling on Grigg et al.'s (2003) fields was done in the late fall and measurements were taken beginning after planting corn and applying crop nutrients and pesticides in late March 1996 and in late April 1997. However, because of the large amount of rainfall in Louisiana (Bengtson and Carter, 2004) the top clay loam soil aggregates are broken into fine particles which cause sealing (Martinez-Gamino, 1994) thus diminishing the benefits of deep chiseling by the time measurements were taken (Grigg et al., 2003). This may explain the difference between Bengtson et al.'s (1995) and Grigg et al.'s (2003) contradicting results. According to the results by Grigg et al. (2003) however, deep chiseling [just before the growing season] may be necessary if subsurface drainage is to reduce nutrient loss in surface runoff from the Commerce silt loam soil.

2.5.4 Deep Chiseling

To deep chisel a field a farmer attaches short angled subsoil shanks to a tractor tool bar and pulls them through the soil, breaking the soil to at least 30cm below the ground surface (Grigg and Fouss, 2002). Deep chiseling increases infiltration and reduces surface runoff by increasing the vertical component of saturated hydraulic conductivity (K) of the top layer of soil (Kincaid, 2002) and by increasing the maximum surface depressional storage (STMAX) (Kamphorst et al., 2000; Kincaid, 2002; Guzha, 2004). Maximum surface depressional storage is related to the depth of the soil surface depressions and ability of the soil surface to hold/pond water. Roughly tilled fields hold considerable amounts of water in the surface depressions (Idowu et al., 2002; Guzha, 2004) thus reducing surface runoff as opposed to smooth surface fields, which lead to high surface runoff. Some of the ponded water held in the surface depressional storage infiltrates into the subsoil and some evaporates into the atmosphere.

Unfortunately, the benefits of deep chiseling are only temporary because the soil surface seal reforms and soil compaction increases gradually to the previous condition as the fine particles fill the soil pore spaces and surface depressions are smoothed out after subsequent rainfall events (Rao et al, 1998b; Allen and Musick, 2001). The conditions mentioned above will decrease vertical saturated hydraulic conductivity and maximum surface depressional storage (Kincaid, 2002). Currently there is insufficient information available to advise the farmers how often to deep chisel their farm fields to maximize the benefits associated with deep chiseling. Farmers and researchers decide on the frequency based on whether they think there is need to deep chisel based on their farming experience, which may or may not be the best timing.

Therefore, there is need to model the benefits of deep chiseling depending on climatic conditions over time after deep chiseling to determine how often to deep chisel. This requires the use of accurate infiltration models to determine infiltration and runoff from a particular rainfall event at different stages of surface seal reformation to estimate the increased crop yields and reduced pollution benefits.

2.6 Infiltration Models

Like any science, engineering is concerned with explanation and prediction of observed phenomena. A model is any device or mathematical equation that represents an approximation of a real situation. Artificial representation of an event performed with the aid of the developed model is referred to as simulation. Easily measurable parameters are used to estimate the ones that are hard to measure. Modeling can save time and money because it provides the ability to quickly and efficiently analyze or simulate possible multiple design scenarios over long periods of time and compare results to determine the best design for particular soil field and climatic conditions.

For many decades engineers have continued to strive to model the soil water infiltration process with an aim of developing better infiltration models or modifying existing models to improve prediction of infiltration during a particular rainfall event for a given soil.

2.6.1 A Review of the More Widely Used Infiltration Models

Many formulations, both empirical and theoretical have been proposed over the years to attempt to quantify infiltration capacity as a function of time or of total volume of water infiltrated into the soil. The most widely used infiltration models can broadly be classified as those based on the numerical solution of the general one-dimensional porous flow equation e.g. the Richard's equation, those based on the analytical solutions of the physically based Darcy's law such as Philip's equation (*1957*) and Green and Ampt (*1911*), and empirically derived models such as Kostiakov equation (*1932*), Horton equation (*1940*) and Holtan equation (*1961*). Hillel (1982) and Skaggs (1980) give a good review of these infiltration equations. In this section, the symbol F is used to represent the cumulative volume of water infiltrated in time t per unit area of soil surface. Symbol f represents the infiltration capacity, defined as the volume of water entering a unit soil surface area per unit time (Hillel, 1982).

2.6.1.1 Green and Ampt (*1911*) Equation

Green and Ampt equation (*1911*) was the earliest infiltration equation developed (Hillel, 1982). In it's initial form,

$$f = f_c + b/F \tag{2-1}$$

where, b and f_c are the characterizing constants, with f_c ($f = dF/dt$, and $F = \int_0^t f\, dt$) being the asymptotic steady infiltration rate when time t and consequently cumulative volume of water F becomes large (Figure 2-2). This model arises from a mathematical solution of the physically based theories of infiltration, namely Darcy's law yet some of its relationships, which are described in detail later in this chapter, are essentially empirical.

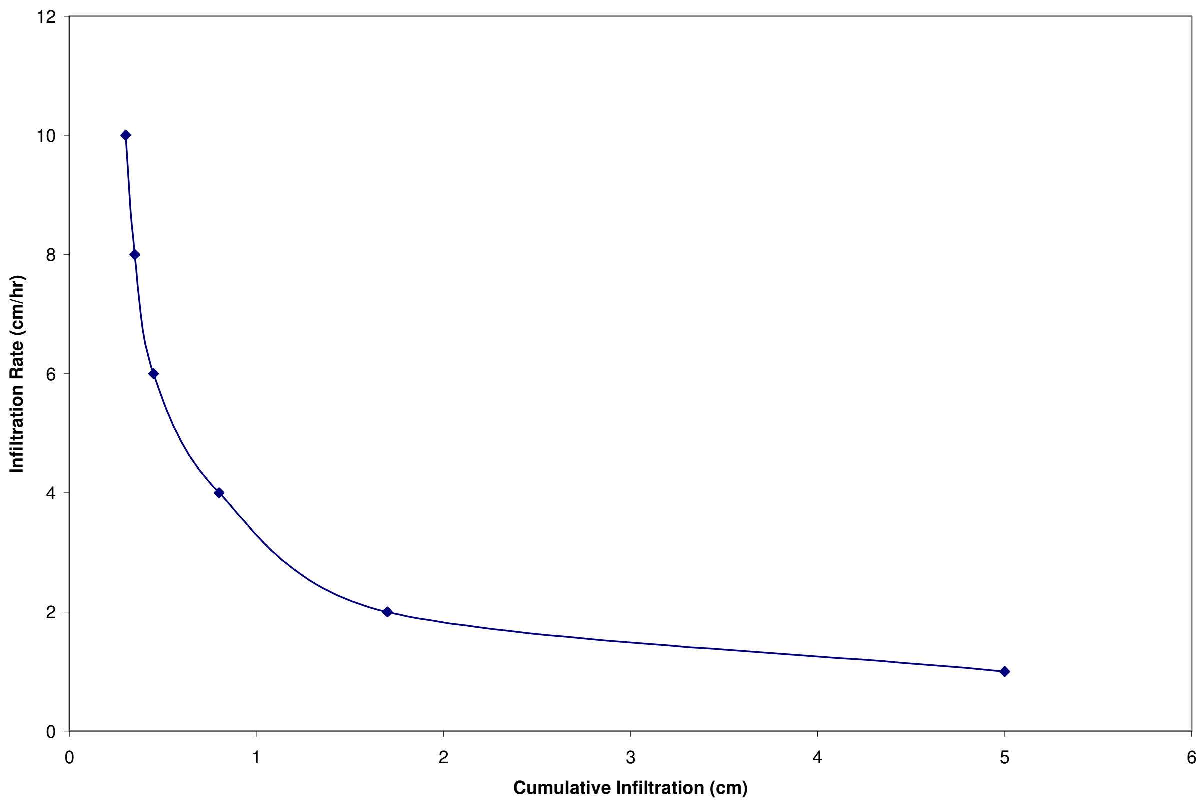


Figure 2-2. Graphical representation of Green and Ampt (*1911*) equation

Equation 2-1 applies well for soils with uniform profiles, profiles that become denser with depth, in other words, profiles whose hydraulic conductivity decreases with depth, and profiles with partially sealed surfaces (Skaggs, 1980). This model assumes surface water ponding in its application. When the rate of water application to the soil, through either rainfall or irrigation, exceeds the infiltration capacity of a soil, surface ponding occurs. On the other hand, the implications of the above advantages is that Green and Ampt does not give good estimates of infiltration rate for soils with non uniform profiles, profiles that become less dense with depth like Commerce silt loam (Rogers et al., 1991) and soils that are prone to surface seal formation like the alluvial soils (Martinez-Gamino, 1994).

For the Commerce silt loam soil [fine silty, mixed, non-acid, thermic Aeric Flivaquent] a southern Louisiana alluvial soil, the top (surface) soil layer is the least conductive (Rogers et al., 1991) due to the formation of soil surface seal caused by the high (about 27%) clay content in the surface layer (Kornecki and Fouss, 2001). Saturated hydraulic conductivity for the Commerce silt loam soil increases with depth for depths from 1.46 cm/hr (0.6 m) to 4.39 cm/hr (1.5 m) and then decreases with depth to 2.88 cm/hr (2.4 m) as determined by Rogers et al. (1991). A tillage practice that has been used by farmers in Louisiana to break the soil surface crust and the hard pan in order to increase infiltration and reduce surface runoff is deep chiseling (Bengtson et al., 1995).

2.6.1.2 Kostiakov (*1932*) Equation

In 1932, Kostiakov developed a strictly empirical equation, which is not tied to soil properties.

$$f = Bt^{-n} \qquad (2\text{-}2)$$

where B and n are constants based on the data collected. The advantages of Equation 2-2 include being empirical it is a quick approximate method to determine infiltration for a particular location and at a particular time. However, this equation is useful for purely horizontal water absorption but can not work for downward infiltration because this equation provides an infinite initial infiltration rate, which approaches zero as time increases rather than a constant nonzero, f_c (Figure 2-3).

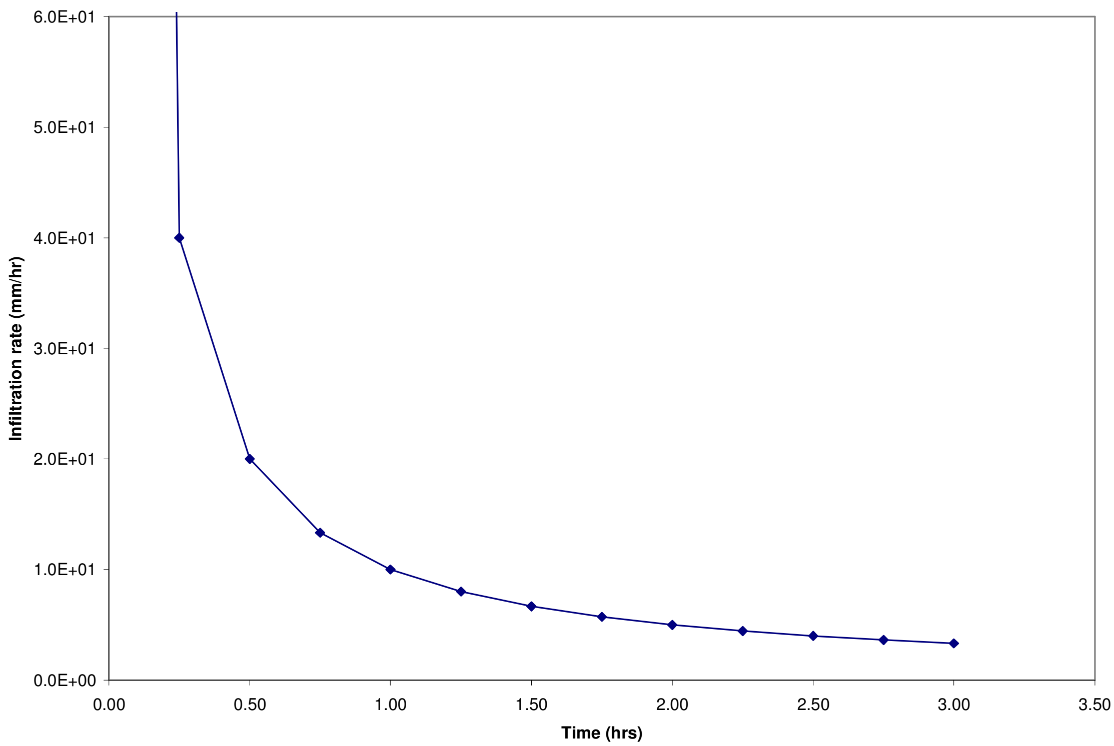


Figure 2-3. Graphical presentation of Kostiakov (*1932*) equation

2.6.1.3 Horton's (1940) Equation

The third equation is the one developed by Horton in 1940 shown below.

$$f = f_c + (f_0 - f_c)e^{-kt} \tag{2-3}$$

where f_c, f_0, and k are the characterizing constants. The constant k determines how fast f decreases from f_0, to f_c. Equation 2-3 like, Kostiakov's equation is an empirical expression selected to fit the desired qualitative shape but is not tied to soil properties. The infiltration capacity at time t=0 is not infinite as in the cases of the Green and Ampt and Kostiakov equations, but it takes a finite value f_0, which is a more realistic and which provides a better description of the infiltration phenomenon under surface ponding (Hillel, 1982) (Figure 2-4). According to Hillel (1982) the problem with Horton's equation is that it is cumbersome in practice, because it contains three constants that must be determined experimentally.

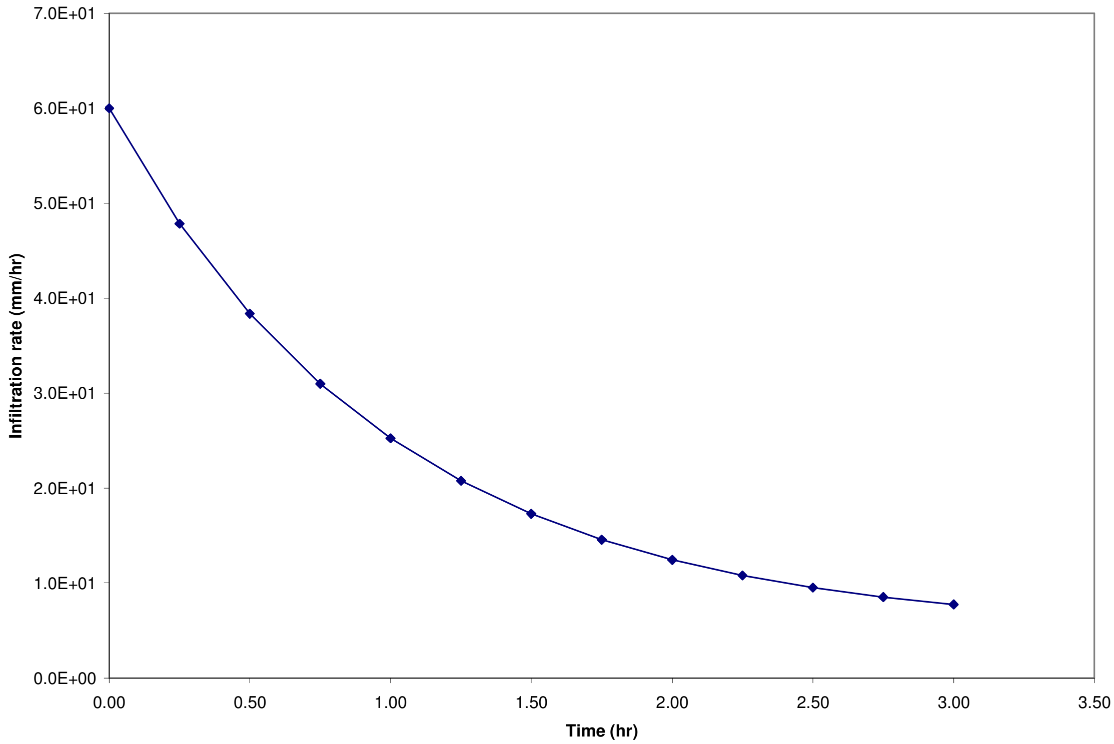


Figure 2-4. Graphical representation of Horton's (1940) equation

2.6.1.4 Philip's (*1957*) Equation

Philips' equation takes the following form,

$$f = f_c + s/2t^{1/2} \qquad (2\text{-}4)$$

where f_c and s are the characterizing constants. This equation, like Green and Ampt, is derived from the physically based theories of infiltration, for example Richard's equation and it gives considerable insight into the processes governing infiltration. Another advantage of Equation 2-4 is that only two constants are required, meaning less work in determining the unknowns (Hillel, 1982). However, Philip's equation represents infiltration capacity at zero time as infinite and it was developed for application in homogeneous soils only (Figure 2-5). This means that it cannot be used in nonhomogeneous soils and soils with surface seals and crusts. Additionally, Philip's equation is only valid for short-term infiltration, which can limit its usefulness in field applications where infiltration may last for long time periods (Williams et al., 1998).

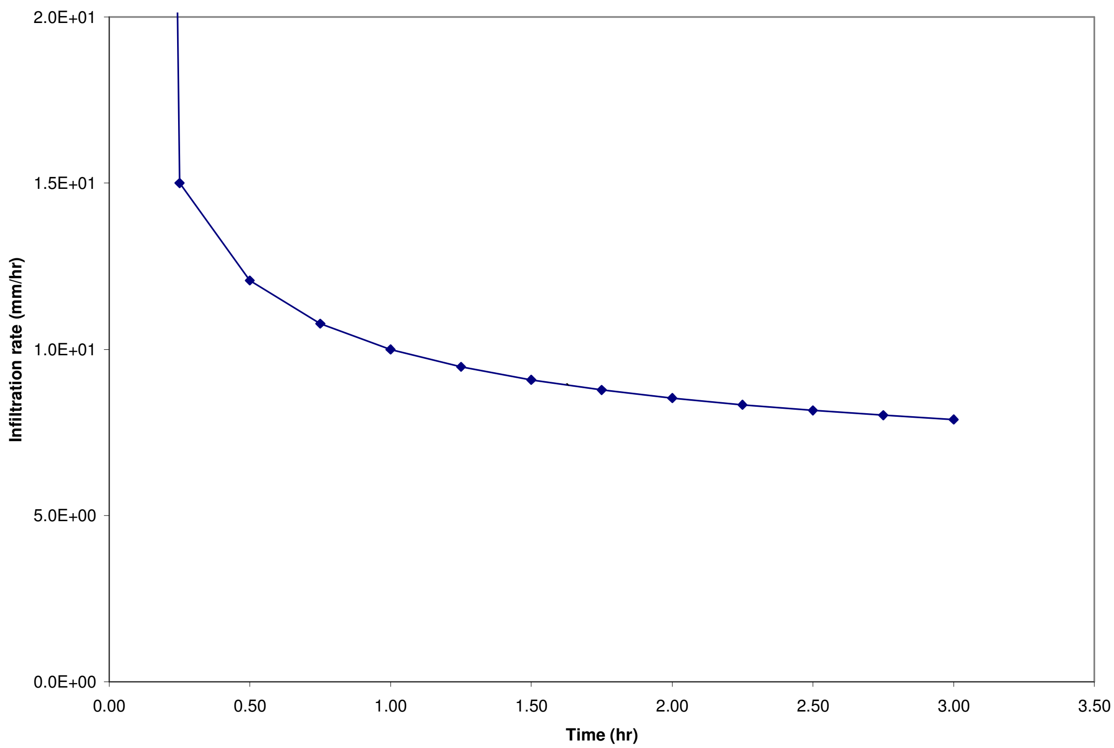


Figure 2-5. Graphical representation of Philip's (*1957*) equation

2.6.1.5 Holtan's (*1961*) Equation

The equation proposed by Holtan in 1961 is as shown below.

$$f = f_c + a(M\text{-}F)^n \tag{2-5}$$

where f_c, a, M, and n are constants. M is the water-storage capacity of the soil above the restrictive layer. In other words M is the difference between total porosity and initial soil moisture content expressed in units of equivalent depth (Hillel, 1982). Holtan's equation takes a finite value when time or cumulative infiltration is zero, which is a more realistic for flux-controlled type of beginning infiltration (Hillel, 1982) (Figure 2-6). Equation 2-5 is an empirically based equation like the Kostiakov (*1932*) and Horton (*1940*) equations. These equations are site specific and are not transferable to other areas of similar conditions. Other limitations of Equation 2-5 include the fact that the meaning of M for a soil without a restrictive layer is not clearly defined. What is not explicitly stated in Holtan's equation is the fact that the equation only holds for the range $0 \leq F \leq M$, since $f = f_c$ can only occur at the single point $F = M$ (Hillel, 1982). For $F > M$, the quantity $(M - F)^n$ becomes either positive and increasing, negative and decreasing, or imaginary, depending on whether n is even, odd, or fractional respectively (Hillel, 1982). Also the large number of characterizing constants sometimes makes it hard to use Holtan's equation.

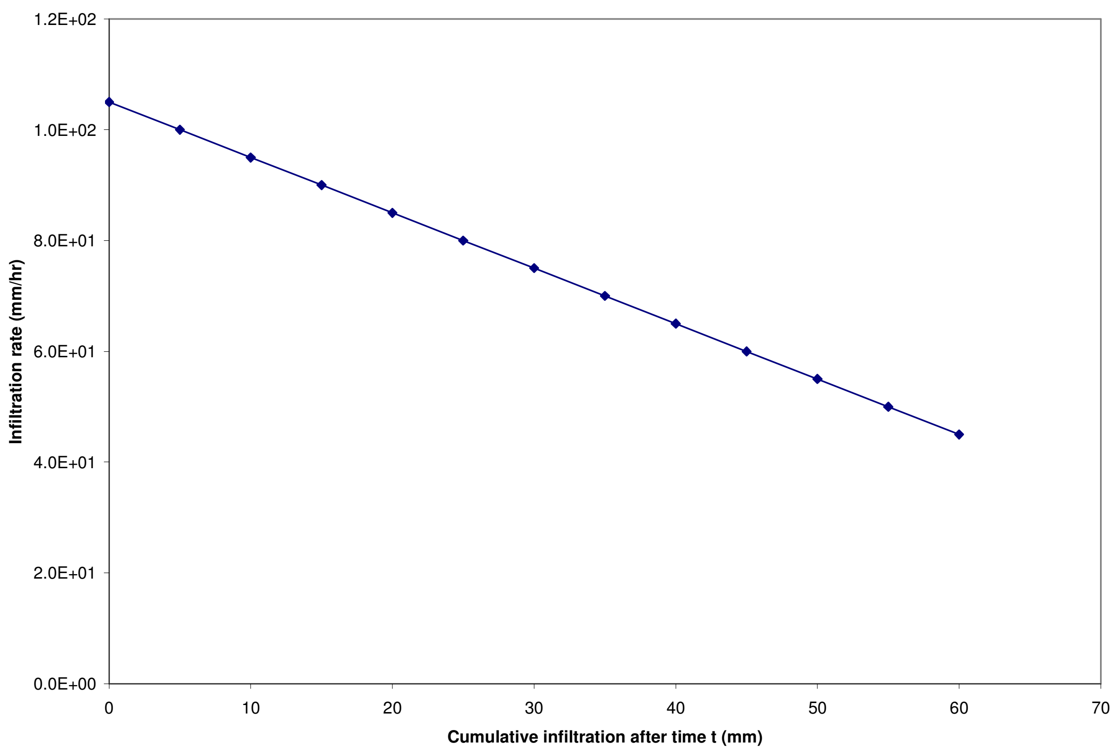


Figure 2-6. Graphical representation of Holtan's (*1961*) equation

2.6.1.6 Curve Number (CN) Approach

The curve number (CN) approach is a runoff approach and not an infiltration approach (Haan et al., 1994). Curve number tables are available for typical land-use relationships and specific assumed percentages of impervious area to aid in the prediction of infiltration. Whereas this is a quick method for calculating infiltration rates, it is only an approximate method because the curve numbers used are not particular to any specific region (Haan et al., 1994).

2.6.1.7 Richard's Equation

A more comprehensive and accurate infiltration rate model that can be employed is the Richard's equation (Skaggs, 1980). Richards's equation is a partial differential equation for one-dimensional vertical flow resulting from a combination of Darcy's law and the law of conservation of mass (Hillel, 1982). In order to use Richard's equation, it must be solved first either analytically or using numerical methods such as finite element or finite difference subject to the appropriate initial and boundary conditions. However, because of the nonlinearity in the Richards equation, numerical methods sometimes result in problems of convergence (Zhao et al., 2000). Detailed unsaturated soil hydraulic property inputs are required to solve the Richards equation, which limit its use because these properties are generally unknown and expensive to measure (Skaggs, 1980) in addition to the required extensive user training (Zhao et al., 2000).

Because of the aforementioned difficulties of using theoretically based equations like the Richards equation, the approximate equations described above and their modifications are mainly used to determine the infiltration rates in soil and water hydrologic models (Skaggs, 1978; Beasley et al., 1981; Ward et al., 1988). Of all the approximate equations described, Skaggs (1980) chose to use the Green and Ampt equation in a hydrologic model, DRAINMOD because “it appears to be the most flexible in describing infiltration under varied initial, boundary, and soil profile conditions”, which makes it an attractive method for field operations.

2.7 DRAINMOD Description

DRAINMOD is a computer model that was developed at North Carolina State University in the late 1970s (Skaggs, 1978). This model is based on the water balance in the soil profile and uses long-term (20 to 40 years) climatological records to simulate the performance of drainage and water table control systems on a continuous basis. DRAINMOD predicts surface runoff, water table depth, drainage outflow, soil water content, evapotranspiration (ET) and infiltration on hourly, daily, monthly or an annual basis in response to given soil properties, crop variables, climatological data, and site parameter inputs. This model was developed for soils with natural or induced shallow water tables and contains a network of parallel drainage ditches or subsurface drains.

DRAINMOD has been used as a tool to optimize the design and evaluation of water management systems such as surface and subsurface drainage systems an example of which is shown in Figure 2-7. This model does not include complex numerical methods, which require long computer time to simulate long-term events, but uses approximate methods (USDA, 1994) to quantify the hydrologic components: subsurface drainage, sub irrigation, infiltration, evapotranspiration (ET) and surface runoff as shown in Figure 2-7 below.

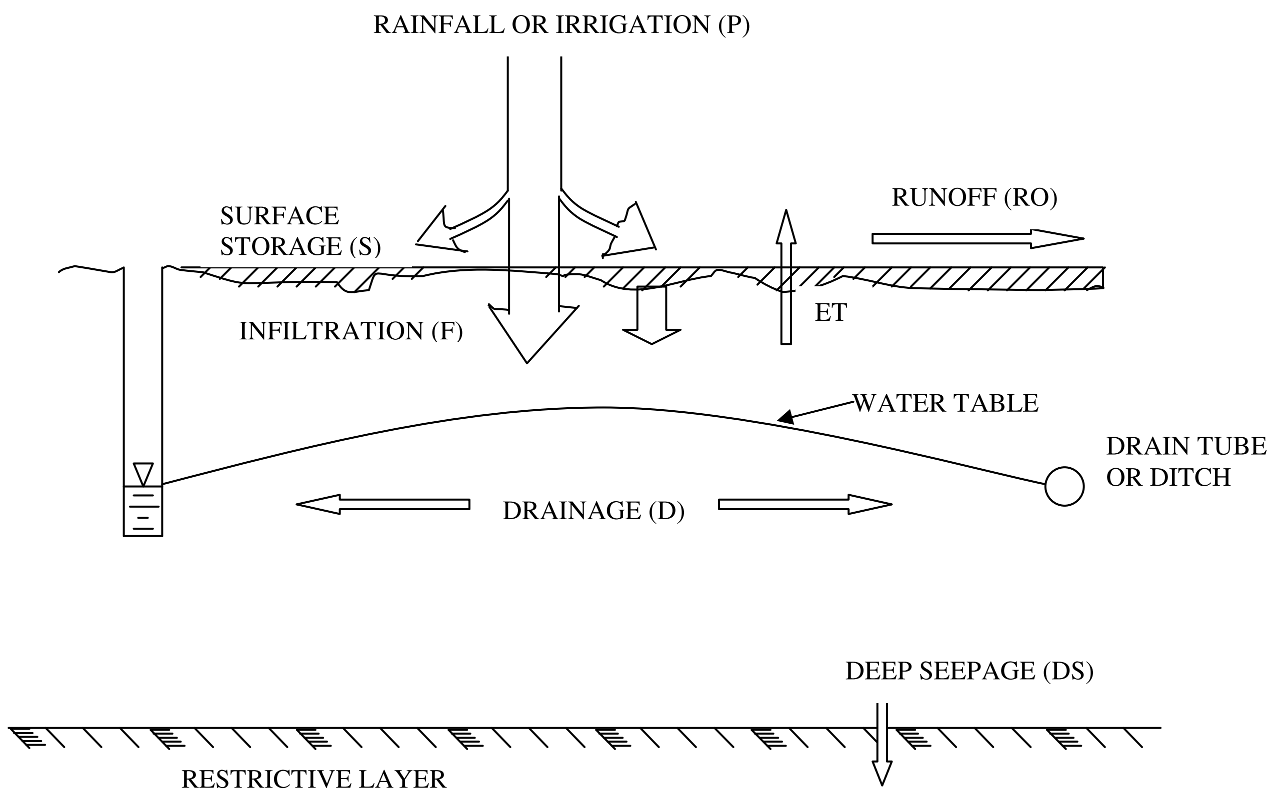


Figure 2-7. Schematic of water management system with drainage to ditches or drain tubes. Components considered in the water balance are shown in the diagram (Skaggs, 1980).

DRAINMOD has been tested and verified in different regions (Gayle et al., 1985; Skaggs and Nassehzadeh-Tabrizi, 1986; Fouss et al., 1987; McMahon et al., 1988; McCarthey and Skaggs, 1989; Cox et al., 1994). Fouss (1985) modified DRAINMOD into a dynamic simulation model for soil-water management system, including an automatic-control subroutine. Later Fouss et al. (1989) modified DRAINMOD to predict daily fluctuations in the water table midway between drains for an automatically operated, sump-controlled water table management system. DRAINMOD version 5.1, in which the infiltration subroutine modifications will be made, has new extensions to predict the movement of salt (DRAINMOD-S) and nitrogen (DRAINMOD-N) in shallow water table soils (Skaggs and Fernandez, 1998).

The main goal of this study was to modify the current DRAINMOD model by incorporating the effects of deep chiseling and rainfall intensity to improve its estimation or prediction of infiltration and surface runoff. Therefore, detailed discussion of DRAINMOD components, as described by Skaggs (1980), in the next section is limited to those components that affect the calculation of infiltration and surface runoff or components that involve water balance at the soil surface. Detailed discussion of the remaining components considered is given by Skaggs (1980).

2.7.1 Water Balance Equations in DRAINMOD Model

The basic relationship in the DRAINMOD model is a water balance for a thin section of soil of unit surface area, which extends from the restrictive layer to the surface and located midway between adjacent drains. The water balance for a time increment of Δt may be expressed as,

$$\Delta V_a = D + ET + DS - F \qquad (2\text{-}6)$$

where ΔV_a is the change in the air volume (cm), D is the lateral drainage (cm) from (or subirrigation into) the section, ET is evapotranspiration (cm), DS is the deep seepage (cm), and F is infiltration entering the section in time increment Δt.

The amount of runoff and storage on the surface is calculated from a water balance at the soil surface for each time increment and is written as,

$$P = F + \Delta S + RO \qquad (2\text{-}7)$$

where P is the rainfall or surface irrigation (cm), F is infiltration (cm), ΔS is the change in volume of water stored on the soil surface (cm), and RO is runoff (cm) during time Δt.

The time increment used for the water balance equation is dependent upon the amount of rainfall and drainage and evapotranspiration rates (Skaggs, 1980). The basic time increment used in Equations 2-6 and 2-7 is one hour. When rainfall does not occur and when drainage and ET rates are slow Equation 2-6 uses a time increment of 1 day but if drainage is rapid and it does not rain, a time increment of 2 hours is used. However, when rainfall rates exceed the maximum infiltration rate, time increments of 3 minutes or less are used to calculate F. Rearranging Equation 2-7, RO is calculated thus,

$$RO = P - F - \Delta S \tag{2-8}$$

Therefore the components required to compute surface runoff are basically rainfall or precipitation, infiltration, and surface depression storage. Methods used to calculate the terms on the right hand side of Equation 2-8 are discussed in the next sections.

2.7.2. Precipitation

Rainfall records are one of the major inputs of the DRAINMOD model. The accuracy of the model prediction for infiltration, surface storage, and hence runoff depends to a great extent on the complete description of rainfall. A short time increment for rainfall input data allows better estimates for the model components listed above than with long time increment rainfall data.

DRAINMOD uses hourly rainfall because hourly rainfall data was readily available in many locations in the United States at the time of its development (Skaggs, 1978). Hourly rainfall data for most locations in the United States could be obtained from the National Weather Service at Asheville, North Carolina. The rainfall distribution within the hour is assumed to be uniform, which may not give a complete description of the within hour variation in rainfall. Shorter rainfall time increments are easily available now because of the increased use of data loggers at weather stations throughout the United States.

Hourly rainfall rates may not be a problem in accurate estimation of infiltration and runoff by the current DRAINMOD model for areas where the amount of precipitation is low and the rainfall distribution is relatively uniform. Hourly rainfall rates may result in inaccurate prediction of infiltration and runoff in the southeastern United States where rainfall amounts are significant (Bengtson and Carter, 2004) and where all rainfall in a given event may fall within minutes (LSU AgCenter Climate, 2004). For example the annual precipitation average for Louisiana is approximately 1550 mm (Bengtson and Carter, 2004) and the distribution of rainfall within any particular hour appears to be random and is rarely uniform. In such a case if the amount of rain is significantly high say during only five minutes and an hourly rainfall rate is used in the model, it may lead to overestimating infiltration while underestimating surface runoff as shown in Figure 2-8.

Actual minute rainfall data in Figure 2-8 was obtained from Louisiana Agriclimatic Information Website for the 7th hour on May 12th, 2004 (LSU AgCenter Climate, 2004). Dividing the hourly rainfall by 60 minutes of the hour generated the assumed uniform minute rainfall in DRAINMOD model. Finally the infiltration rates (mm/min) were generated from the graph information on the infiltration rate versus time for a sandy loam soil initially drained to equilibrium to a water table 1.0 m deep (Skaggs, 1980). The shaded region shows the amount by which infiltration is overestimated or runoff underestimated.

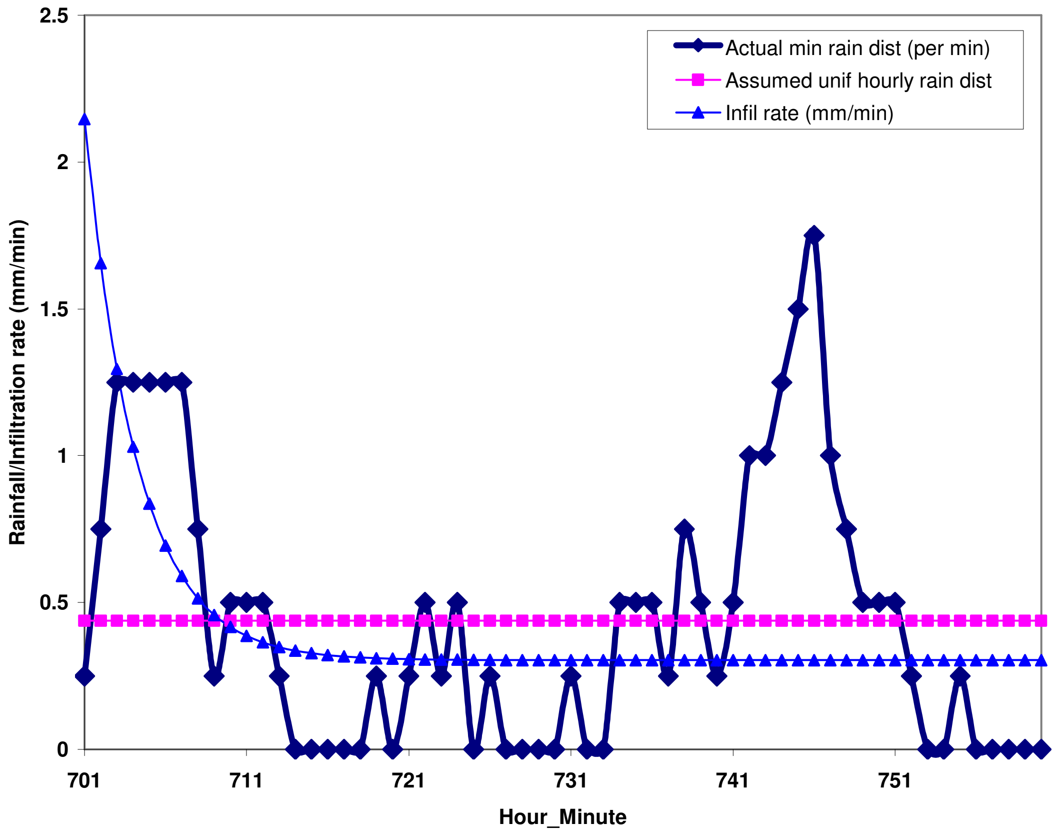


Figure 2-8. Comparison of infiltration and runoff for the actual and assumed uniform rainfall rates (using data from LSU AgCenter Climate, 2004; Skaggs, 1980).

2.7.3. Surface Depression Storage

Soil surface depression storage can have a significant effect on runoff. The maximum average depth of depression storage (STMAX) that must be satisfied before runoff can begin characterizes surface drainage. Depression storage is composed of a micro component, which represents storage in small depressions due to surface structure and cover and a macro component, which is due to larger surface depressions that may be altered by land forming and grading (Skaggs, 1980). Another storage component that must be considered is the depth of surface water accumulated before surface runoff begins often referred to as surface detention (Skaggs, 1980). According to Skaggs (1980) surface detention is neglected in the current DRAINMOD model, which assumes that runoff moves immediately from the surface to the outlet because the flow paths are relatively short and therefore the water volume is assumed to be small for the field size units considered in this model.

When rainfall occurs at a greater intensity than the infiltration capacity the extra water fills the soil surface depressions after which runoff begins. At the end of a rainfall event, water remains stored in the depressions until it either infiltrates into the soil or evaporates (ET) from the surface (Skaggs, 1980) as shown in Figure 2-7.

In the current DRAINMOD model the maximum depression storage (STMAX) is assumed to be evenly distributed over the entire farm field and it is further assumed constant irrespective of factors that may affect depression storage depth such as time, climatic conditions, or tillage operations. However, this is not the case in reality.

2.7.3.1 Variation of STMAX during Crop Growing Seasons

Micro-storage is affected by cultivation practices and varies throughout the crop-growing season. According to Gayle and Skaggs (1978), the micro storage component varied from 0.1 cm for soil surfaces that have been smoothed by weathering to several centimeters for rough tilled land because the higher the surface roughness the greater the depression storage [STMAX] (Guzha, 2004). From their study, Gayle and Skaggs (1978) further found that after land preparation tillage in February the average depth of storage generally decreased exponentially from a maximum to a steady minimum value one and half months after harvesting in mid September as shown in Figure 2-9. Figure 2-9 does not include deep chiseling operation.

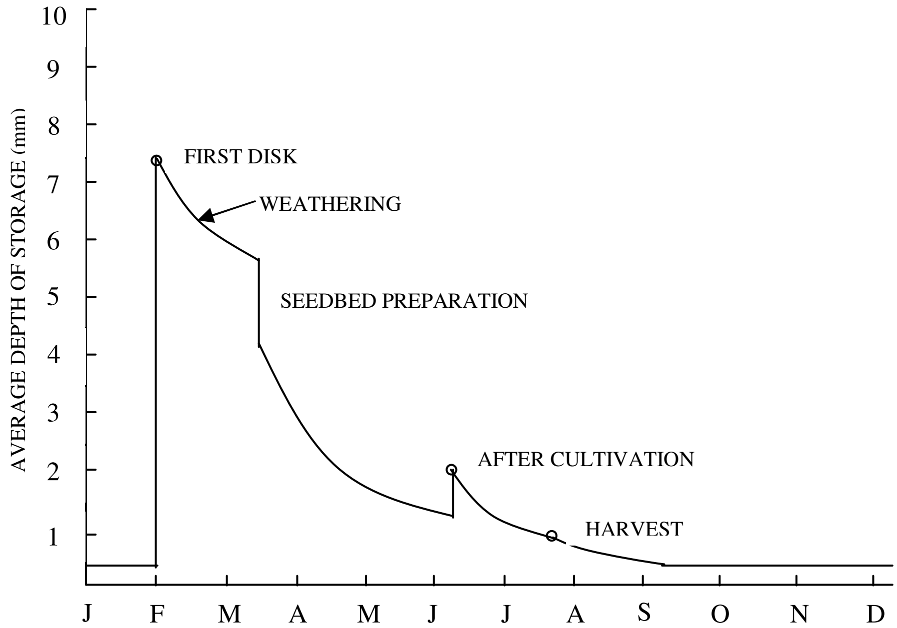


Figure 2-9. Schematic of annual variation in micro-storage for a Cape Fear clay loam soil (Recreated from actual graph – Gayle and Skaggs (1978)).

Guzha (2004) also found that surface depression storage decreased exponentially with increase in cumulative rainfall after tillage operations [especially on bare soil surface]. Moore and Larson (1979) similarly reported that micro-relief storage (STMAX) increases significantly by plowing [a tillage operation], but is substantially reduced by subsequent rainfall. Therefore assuming a constant value for STMAX would lead to under-prediction or over-prediction of infiltration and runoff by the DRAINMOD model, depending on the crop- growing season and tillage operation.

2.7.4. Infiltration Calculation in DRAINMOD Model

The common equations used to characterize infiltration are discussed in section 2.6.1 above. DRAINMOD model uses the modified Green and Ampt equation to calculate infiltration because of the reasons described in the infiltration model review given in the previous section of this chapter.

2.7.4.1 Green and Ampt Equation Derivation

The description of this derivation is as given by Skaggs (1980). Green and Ampt equation was initially derived for deep homogeneous profiles with uniform antecedent water content. Water is assumed to enter the soil as slug flow resulting in a sharply defined wetting front, which separates a zone that has been wetted from a completely uninfiltrated zone (Hillel, 1982) as shown in Figure 2-10.

Applying Darcy's law for vertical infiltration gives:

$$q = -KdH/dz = -Kd(H_p - z)/dz \tag{2-9}$$

where q is the flux, H the total hydraulic head*, H_p is the pressure head, and z is the vertical distance from the soil surface.

Given simplifying conditions for a ponded soil surface result in:

$$f = -K_s(H_2 - H_1)/L_f \tag{2-10}$$

where f is the infiltration rate, which is equal to the downward flux , q (cm/hr), L_f is the length of the wetted zone (cm), K_s is the hydraulic conductivity of the wetted or transmission zone (cm/hr), H_1 is the hydraulic head at the soil surface, and H_2 is the hydraulic head at the wetting front.

If the soil surface is taken as a reference point, $H_1 = H_0$, the ponded water depth and $H_2 = h_f - L_f$ where h_f is the soil water pressure head at the wetting front. Substituting the values of H_1 and H_2 into Equation 2-10 results in,

$$f = -K_s(h_f^{\dagger} - L_f - H_0)/L_f \tag{2-11}$$

---

* Hydraulic head H is the sum of a pressure head H_p and a gravity head H_g (Hillel, 1980)
† h_f is a negative quantity (Hillel, 1980).

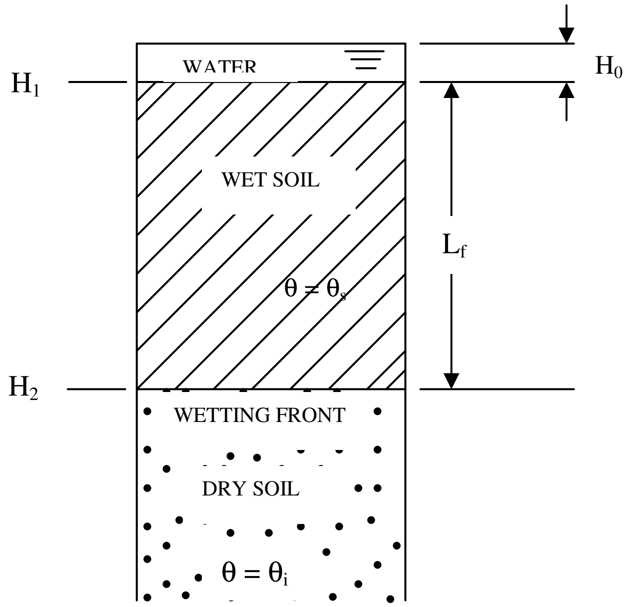


Figure 2-10. Green and Ampt equation definition sketch (Skaggs, 1980).

Substituting a positive quantity, S_{av}, the effective suction at the wetting front for h_f ($h_f = -S_{av}$) in Equation 2-11 and multiplying all through by the negative one (-1) gives,

$$f = K_s(S_{av} + L_f + H_0)/L_f \tag{2-12}$$

Cumulative infiltration, F, at any time, may be expressed as, $F = (\theta_s - \theta_i)L_f = ML_f$, where θ_s is the volumetric water content in the wet zone, θ_i is the initial water content and M is the initial soil water deficit (fillable porosity). Assuming H_0 is negligible compared to $S_{av} + L_f$ and substituting $L_f = F/M$ into Equation 2-12 gives the Green and Ampt equation (often abbreviated as Green-Ampt equation):

$$f = (K_s M S_{av})/F + K_s \tag{2-13}$$

The original derivation by Green and Ampt assumed total saturation* behind the wetting front. In practice, because of air entrapment, the soil water content, θ_s, may not reach saturation but may attain some maximal value lower than saturation known as

* Total saturation is guaranteed only when a soil sample is wetted under vacuum (Hillel, 1980).

"satiation" (Hillel, 1980). Similarly, K_s is expected to be less than saturated hydraulic conductivity. For a given soil with given initial water content infiltration rate becomes

$$f = A/F + B \tag{2-14}$$

where $A = K_s\, M\, S_{av}$ (cm^2/hr) and $B = K_s$ (cm/hr) are the Green-Ampt parameters, which depend on the soil properties (K_s), initial water content (M) and distribution (S_{av}) and surface conditions such as cover and crusting, which affect K_s.

Green-Ampt equation assumes a ponded surface. Therefore, infiltration rate is equal to infiltration capacity at all times. However, for rainfall infiltration where there may be long periods of infiltration at less than the maximum rate, infiltration rate is assumed equal to the rainfall rate until it exceeds the capacity as predicted by Equation 2-13 (Skaggs, 1980). Based on the previous work (Skaggs, 1980), a further Green-Ampt equation assumption in DRAINMOD model is that infiltration rate can be expressed in terms of cumulative infiltration, F, alone, irrespective of the application rate as shown in Figure 2-2.

2.7.4.2 Using Green-Ampt Equation in DRAINMOD Model

According to Skaggs (1980) DRAINMOD model requires inputs for infiltration in the form of a table of A and B versus water table depth (WTD) as shown in Table 2-1. During a rainfall event, A and B values are interpolated from the table for the appropriate water table depth at the beginning of the rainfall event.

Table 2-1. Example of Green-Ampt parameters matrix (Skaggs and Fernandez, 1998)

Water table depth (WTD) (cm)	A Coefficient (cm^2/hr)	B Coefficient (cm/hr)
0	0.000	0.000
50	1.200	1.000
100	3.300	1.000
150	6.000	1.000
200	9.200	1.000
500	25.000	1.000
1000	25.000	1.000

An iteration process is used with Equation 2-14 to determine the cumulative infiltration (F) at the end of hourly time intervals. When the rainfall rate exceeds the infiltration capacity (f) given by Equation 2-14, Equation 2-7 is applied to conduct a water balance at the surface for time increments of 3 minutes. The excess rainfall fills the surface depressions to a maximum depth (STMAX) for a given field after which additional water is apportioned to surface runoff. At the end of every hour, infiltration and surface runoff are accumulated and the current depth of surface storage read to give the predictions of these components hourly.

Infiltration is accumulated hourly and used in Equation 2-14 until rainfall stops and all water stored in the surface depressions has infiltrated. Similarly the same values of parameters A and B are used as long as the rainfall event lasts, with an exception when the water table rises to the ground surface, in which case A is set to A = 0, and B is set equal to the sum of the drainage (D), ET and deep seepage rates shown in Equation 2-6 and illustrated by Figure 2-7. An infiltration event is assumed to terminate and new values of A and B evaluated for succeeding rainfall events at least two hours (arbitrary selected) after a rainfall event and/or without surface water for infiltration.

Methods for determining the Green-Ampt parameters (A and B) from infiltration measurements and from basic soil properties are discussed in detail by Skaggs (1980). According to Skaggs (1980) an added advantage of Green-Ampt equation is that the equation parameters (A and B) have physical significance and can be computed from the soil properties (K_s and S_{av}). In this research, parameters A and B were determined from field measurements of soil parameters using methods like those proposed by Bouwer (1966). A sensitivity analysis for the Green-Ampt equation parameters (A and B) by Skaggs (1980) showed that predicted infiltration and runoff amounts and rates are most sensitive to errors in fillable porosity (M) and saturated hydraulic conductivity (K_s) and less sensitive to errors in suction at the wetting front (S_{av}). This information is important in determining the parameters that need to be monitored closely to reduce infiltration and runoff prediction errors by DRAINMOD model.

The current version of DRAINMOD model assumes that the parameters A and B matrix for any given soil (Table 2-1) are constant (Skaggs and Fernandez, 1998). In other words, parameters A and B do not change with time or tillage operations and surface sealing among other factors. However, these values change depending on the farming operations such as tillage, which affect the soil properties such as saturated hydraulic conductivity (K_s) and suction at the wetting front (S_{av}). However, because prediction of infiltration amounts and runoff amounts and rates by Green-Ampt model in DRAINMOD model are less sensitive to errors in S_{av} and because effective suction at the wetting front is difficult to determine (Skaggs, 1980), only the variation of K_s with farming operations were considered. One of the farming practices used that can change K_s is deep chiseling.

2.8 Variation of Saturated Hydraulic Conductivity (K) after Deep Chiseling

Deep chiseling increases infiltration and reduces surface runoff by increasing the "effective" vertical component of saturated hydraulic conductivity (K) of the top layer of soil (Kincaid, 2002). Unfortunately, the benefits of deep chiseling in increasing K and hence infiltration are only temporary because the soil surface seals (Martinez-Gamino, 1994; Slattery and Bryan, 1994; Assouline and Mualem, 2002) and soil compaction increases gradually to the previous condition as the fine particles fill the soil pore spaces and surface depressions are smoothed out after subsequent rainfall events (Rao et al, 1998; Allen and Musick, 2001). The above conditions will decrease vertical saturated hydraulic conductivity (Kincaid, 2002).

Because the prediction of infiltration and runoff by Green-Ampt equation in DRAINMOD model is most sensitive to errors in K_s (Skaggs, 1980), it is necessary to measure (or model) and use the current K_s after deep chiseling a soil. Saturated hydraulic conductivity (K) changes over time depending on the amount and intensity of rainfall events after deep chiseling (Rao, et al., 1998). Information from DRAINMOD model simulations will aid engineers and farmers to determine how often to deep chisel depending on the type of soil for given climatic conditions.

Measurement of saturated hydraulic conductivity of soil in the field is accomplished by using different methods, which often have different operating ranges, flow geometries, boundary conditions, sample sizes, and underlying assumptions. Selecting the suitable method for particular soil and site conditions is important in obtaining representative estimates of K.

2.9 A Review of in situ Vertical Saturated Hydraulic Conductivity Measurement Methods in the Vadose Zone

There is no one method that is suitable under all conditions. The suitability of any one method depends on the soil type, whether the soil is saturated or unsaturated, availability of labor force and the purpose for which the data is required. A detailed description of field methods for determining saturated hydraulic conductivity in the vadose zone is given in Test Method D 5126 (ASTM Standards, 1998). These methods include infiltrometer, air-entry permeameter and borehole permeameter test methods. The advantages and limitations of each method are given in Table 2-2. Before giving a summary of these methods, a clear distinction needs to be made between "true saturated" (K_s) and "field-saturated" (K) hydraulic conductivity.

Because of the entrapped air, true saturated conditions rarely occur in the vadose zone except where restrictive layers result in perched water tables (Bouwer, 1966). The entrapped air prevents water movement in air-filled pores, which consequently, may reduce the hydraulic conductivity measured in the field by as much as 50 percent compared to conditions when trapped air is not present (Reynolds and Elrick, 1986).

2.9.1. Single Ring Infiltrometer

The single ring infiltrometer, proposed by Bouwer (1986), usually consists of a cylindrical ring 30 cm or larger in diameter driven several centimeters into the soil. Water is ponded within the ring above the soil surface. For the constant head measurements, the volumetric rate of water added to the ring to maintain a constant head within the ring is measured. On the hand, for a falling head test, the flow rate is measured by measuring the rate of decline of the water level within the ring. Infiltration is stopped after the flow rate has approximately attained a steady state.

2.9.2. Double Ring Infiltrometer

Bouwer (1986) proposed double ring infiltrometer method, just like the single ring infiltrometer method. The principles of operation of double ring infiltrometer method are similar to the single ring infiltrometer except that an outer ring is included to ensure that one-dimensional downward flow exists within the tested horizon of the inner ring. The advantages and limitations of this method are given in Table 2-2.

Table 2-2. Review and comparison of test methods for measuring saturated hydraulic conductivity in the vadose zone (ASTM Standards, 1998)

Characteristics	**Single ring infiltrometer**	**Double ring infiltrometer**	**Double-tube method**	**Air-entry permeameter**	**Borehole permeameter**	**Empirical equations**
Relative accuracy	Low	Fair	Fair	Good	Good	Low
Relative cost	Low	Low to moderate	Moderate	Moderate	Low to moderate	Low
Time required at $K_{fs} = 10^{-5}$ cm/s	Less than 4 hrs	Less than 4 hrs	4 hrs to 1 day	Less than 4 hrs	Less than 4 hrs	4 hrs
Depth of testing	Surface	Surface	0 to 1ft	0 to 1ft	Any	Any
Advantages	Simple apparatus, can estimate K_{fs} from infiltration data, can increase diameter to reduce scale effects and edge effect	Similar to single ring but more accurate in measuring vertical K_{fs}	Can measure K_{fs} to deeper layers	Measures for vertical K_{fs} only, accounts for capillary effects	Accounts for capillary effects	Simple, rapid
Limitations	Lateral flow affects accuracy, measures infiltration not Kfs, surface crust reduces infiltration, measured on surface of soil only	Same as single ring except that the outer ring reduces the lateral flow effects	Cumbersome apparatus, time consuming numerical solution	Sometimes difficult to drive tube, difficult to identify wetting front in the wet soil	Must assume ratio of capillary to flux effects, difficult to predict, requires description data	Low accuracy

2.9.3. Double Tube Test Method

This method, proposed by Bouwer (1961) and used by Bouwer (1962, 1964), is used to measure both the horizontal and vertical field-saturated hydraulic conductivity in the vadose zone. Double tube test method uses two coaxial cylinders positioned in an auger hole. The difference between the rate of flow in the inner cylinder and the simultaneous rate of combined flow from the inner and outer cylinders is used to calculate the field-saturated hydraulic conductivity. See Table 2-2 for the advantages and limitations of this method.

2.9.4. Air-entry Permeameter

Air-entry permeameter method, proposed by Amoozegar and Warrick (1986), is same as single infiltrometer in design and operation because the volumetric flux of water into the soil within a single permeameter ring is used to calculate field-saturated conductivity. The primary differences between the two methods are that the air-entry permeameter usually penetrates deeper (15-25 cm) into the soil profile and also measures air-entry pressure of the soil. Air-entry pressure is used as an approximation of the wetting front pressure head for the determination of the hydraulic gradient, and consequently field saturated hydraulic conductivity.

2.9.5. Borehole Permeameter

Borehole permeameter methods consist of many test designs, methods of operation, and methods of solution. The common feature among the different methods is that the rate of water infiltration into a cylindrical borehole is used to determine field-saturated hydraulic conductivity. Examples of the borehole permeameter methods are the constant-head borehole infiltration test.

2.9.6. Empirical Methods

A number of empirical methods have been developed for estimation of saturated hydraulic conductivity from grain or particle size data. A summary of some of earlier empirical equations for estimation of saturated conductivity is given in Table 2-3 below.

Table 2-3. Early models for estimating hydraulic conductivity or permeability using particle size distribution data

Model	Parameters used	Investigators
$K^{*\dagger} = Cd^2_{10}$	**K = hydraulic conductivity (cm/s)** C= constant, 100-150 ($cm^{-1}s^{-1}$) for loose sand d_{10} = particle size corresponding to 10 % passing (cm)	Hazen (1892)
$k = 760\ d^2e^{-1.3\sigma}$	k = permeability (dracys) σ = log standard deviation of the particle size d = geometric mean grain diameter (mm)	Krumbein and Monk (1942)
$k = (6.45x10^{-4})\ d^2_{10}$	**k = permeability (cm^2)**	Harleman et al. (1963)
$K = Cd^2_{50}$	K = hydraulic conductivity (cm/s) C= constant ($cm^{-1}s^{-1}$) d_{50} = particle size corresponding to 50 % passing (cm)	Masch and Denny (1966)
$K = (\rho g/\mu)\{[d^2\phi^3]/180(1-\phi)^2\}$	d = representative grain diameter [L] K = hydraulic conductivity [L/T] ϕ = total porosity accounting for compaction [dimensionless] ρ = density of fluid [M/L^3] g = gravitational acceleration [L/T^2] μ = dynamic viscosity [M/LT]	Kozeny-Carman (in Bear, 1972)

More recent equations are discussed here and presented in Table 2-4. Alyamani and Sen (1993) proposed a procedure, which relates the hydraulic conductivity to initial slope and intercept of the grain-size distribution curve because the relatively finer grain zone of the grain-size distribution curve plays a more important role in hydraulic conductivity. This fact is supported by many earlier models, which use d_{10} (corresponding to 10% passing of the sample during a sieve analysis) as the effective diameter in

[†] K is the rate at which a liquid can move through a permeable medium (L/T), k is the easy with which a porous medium can transmit a liquid under a gradient (L^2). They are related thus: $K = k\rho g/\mu$

hydraulic conductivity computations (Hazen, 1892; Harleman et al., 1963). This gives very good correlation (correlation coefficient (R) = 0.94) between particle-size distribution and hydraulic conductivity for soils with mostly silt or smaller size soil particles (Alyamani and Sen, 1993).

Kolttermann and Gorelick (1995) developed a fractional packing Kozeny-Carman relation for hydraulic conductivity for a wide range of sediment mixtures regardless of the confining pressure. This model successfully predicted more than 90% of the field data values to one order of magnitude over seven orders of magnitude of spatial variability despite grain-size distributions being estimated by quantitative depositional simulations rather than measured (Kolttermann and Gorelick, 1995). However, actual measured data from the given field area needed for a better validation. Additional research by Arya et al. (1999) led to a computer model that calculates the hydraulic conductivity (K) as a function of water content (θ) directly from the particle-size distribution. The pore flow rate and pore radius of several textural classes did not exhibit a systematic trend, however, the agreement between the predicted and measured K(θ), for individual samples ranged from excellent to poor for all classes with an average root mean square residuals of 0.878 for all the three textural classes (Arya et al. 1999). This model is suitable for both saturated and unsaturated hydraulic conductivity calculations.

Recent research presented new regression-based models that use the combined parameters that characterize textural and hydraulic properties to predict the saturated hydraulic conductivity of compacted soils from grain size distribution (Boadu, 2000). The models used alternative representations of the grain-size distribution, the fractal dimension, and entropy distributions, together with porosity, soil density, and fines content to estimate hydraulic conductivity. These models performed better than the existing models in predicting hydraulic conductivity using information from the grain-size distribution.

Table 2-4. Recent models for estimating hydraulic conductivity or permeability using particle size distribution data

Model	**Parameters definition**	**Investigators**
$K = 1300\{[I_o + 0{,}025(d_{50}-d_{10})]\}^2$	K = hydraulic conductivity (m/day) I_o = intercept of grain size curve (mm) d_{10} = grain size corresponding to 10 % passing (mm) d_{50} = grain size corresponding to 50 % passing (mm)	Alyamani and Sen (1993)
$K_{fp} = (\rho g/\mu)\{[d^2_{fp}\phi^3_{fp}]/180(1-\phi_{fp})^2\}$	d_{fp} = representative (volume weighted) grain diameter, dependent on fractional packing [L] K_{fp} = fractional packing hydraulic conductivity [L/T] ϕ_{fp} = porosity of sediment mixture calculated with fractional packing model [dimensionless] ρ = density of fluid [M/L^3] g = gravitational acceleration [L/T^2] μ = dynamic viscosity [M/LT]	Koltermann and Gorelick (1995)
$K(\theta_I) = (c\phi_e/\pi)\{\mathrm{Sum}\,(R_j^{(x-2)}w_j[0.667en_j^{(1-\alpha j)}]^{(x-2)/2}$ for j = 1 to i	K = hydraulic conductivity [L_wT^{-1}]* θ_I = volumetric water content, ith fraction [$L_w^3L_b^{-3}$] e = void ratio = $(\rho_s - \rho_b)/\rho_b$ [$L_p^3L_s^{-3}$] n_j = number of spherical particles, jth fraction ρ_b = bulk density [$M_sL_b^{-3}$] ρ_s = particle density [$M_sL_s^{-3}$] ϕ = porosity [$L_p^3L_s^{-3}$] i = 1, 2, ……, n α = scaling parameter [dimensionless] x = dimensionless parameter; 4 for cylindrical tubes of uniform diameter c = dimensionless parameter w_j = mass fraction, solid particles. jth fraction [M_s^{-1}] R_j = mean particle radius, jth fraction [L_s]	Arya et al. (1999)
$\ln K = 33.09 + 0.10P - 0.18\phi + 0.33S - 7.36D - 11.09\rho$	D = fractal dimension S = entropy ϕ = fractional porosity [dimensionless] P = percent of fines (%) ρ = soil bulk density (Mg/m^3)	Boadu (2000)

$n_j = 3w_j/4\pi\rho_s R_j^3$

* For dimensional analysis, L =length, M = mass, and T = time, with subscripts b for bulk, e for effective, p for pore, s for solid and saturated, and w for water.

The information on these methods is useful in selecting accurate, cost effective and less labor-intensive vertical saturated hydraulic conductivity measurement methods needed to determine the transient effects of deep chiseling on soil water infiltration.

This study was designed to model the effects of deep chiseling and rainfall intensity on infiltration and runoff within DRAINMOD thereby improving its prediction of infiltration and surface runoff to aid engineers and researchers to design cost effective water management systems, to increase crop production and reduce water pollution. Specifically, the study conducted field experiments using the double-ring infiltrometer to determine the variation of K_s after chiseling depending on cumulative rain since chiseling to help develop a dynamic K_s subroutine. The study also developed and incorporated, a dynamic K_s subroutine in which K_s is allowed to vary depending on cumulative rainfall since deep chiseling, a dynamic STMAX subroutine whereby STMAX changes depending on time after deep chiseling and a five- minute rainfall increment subroutine if hourly rainfall is 2mm or more. DRAINMOD was then validated for each modification made using two years (1995, 1997) of measured field data from USDA-ARS Ben Hur Research site located in Baton Rouge, Louisiana. Finally predicted infiltration and surface runoff by the modified and original DRAINMOD will be compared to quantify the effect of each modification and combined modifications on infiltration and surface runoff.

CHAPTER THREE

MODIFICATION OF DRAINMOD MODEL TO INCORPORATE A FIVE-MINUTE RAINFALL TIME INCREMENT SUBROUTINE

3.1 Introduction

Rainfall records are one of the major inputs of the DRAINMOD model. DRAINMOD is a computer model that was developed at North Carolina State University in the late 1970s (Skaggs, 1978). The DRAINMOD model is based on the water balance in the soil profile and uses long-term (up to 40 years) climatological records to simulate the performance of drainage and water table control systems on a continuous basis. This model predicts surface runoff, water table depth, drainage outflow, soil water content, evapotranspiration (ET) and infiltration on hourly, daily, monthly or an annual basis in response to given soil properties, crop variables, climatological data, and site parameter inputs. The accuracy of DRAINMOD prediction on infiltration, surface storage, and hence runoff depends to a great extent on the accuracy of the rainfall distribution [rainfall intensity] data used. Short time increment rainfall input data would be expected to provide more accurate and more sensitive component [infiltration, runoff, etc] estimations than long time increment rainfall data.

Presently the DRAINMOD model uses hourly rainfall because hourly rainfall data was available in many locations in the United States at the time of its development (Skaggs, 1978). Hourly rainfall data for most locations in the United States could be obtained from the National Weather Service at Asheville, North Carolina. The rainfall distribution within the hour is assumed to be uniform, which may not give a complete description of the within hour variation in rainfall. Shorter rainfall time increments are easily available now because of the increased use of data loggers at weather stations throughout the United States.

Hourly rainfall rates may not be a problem in accurately estimating infiltration and runoff by the current DRAINMOD model for areas where the amount of precipitation is low and the rainfall distribution is relatively uniform. However, hourly rainfall rates may result in inaccurate prediction of infiltration and runoff in the southeastern United States where rainfall amounts are significant (Bengtson and Carter, 2004) and where all rainfall in a given event may fall within minutes (LSU AgCenter Climate, 2004). For example the annual precipitation average for Louisiana is approximately 1550 mm (Bengtson and Carter, 2004) and the distribution of rainfall within any particular hour appears to be random and is rarely uniform. In such a case if the amount of rain is significantly high during a short time period (five minutes) and an hourly rainfall rate is used in the model, it may lead to overestimating infiltration while underestimating surface runoff (Figure 3-1).

Actual minute rainfall data in Figure 3-1 was obtained from Louisiana Agriclimatic Information Website for the 7th hour on May 12th, 2004 (LSU AgCenter Climate, 2004). Dividing the hourly rainfall by 60 minutes of the hour generated the assumed uniform minute rainfall in DRAINMOD model. Finally the infiltration rates (mm/min) were generated from the graph information on the infiltration rate versus time for a sandy loam soil initially drained to equilibrium to a water table 1.0 m deep (Skaggs, 1980). The shaded region shows the amount by which infiltration is overestimated or runoff underestimated by the DRAINMOD model with the assumption of uniform rainfall intensity, which would be even worse for the Commerce silt loam soil in Louisiana.

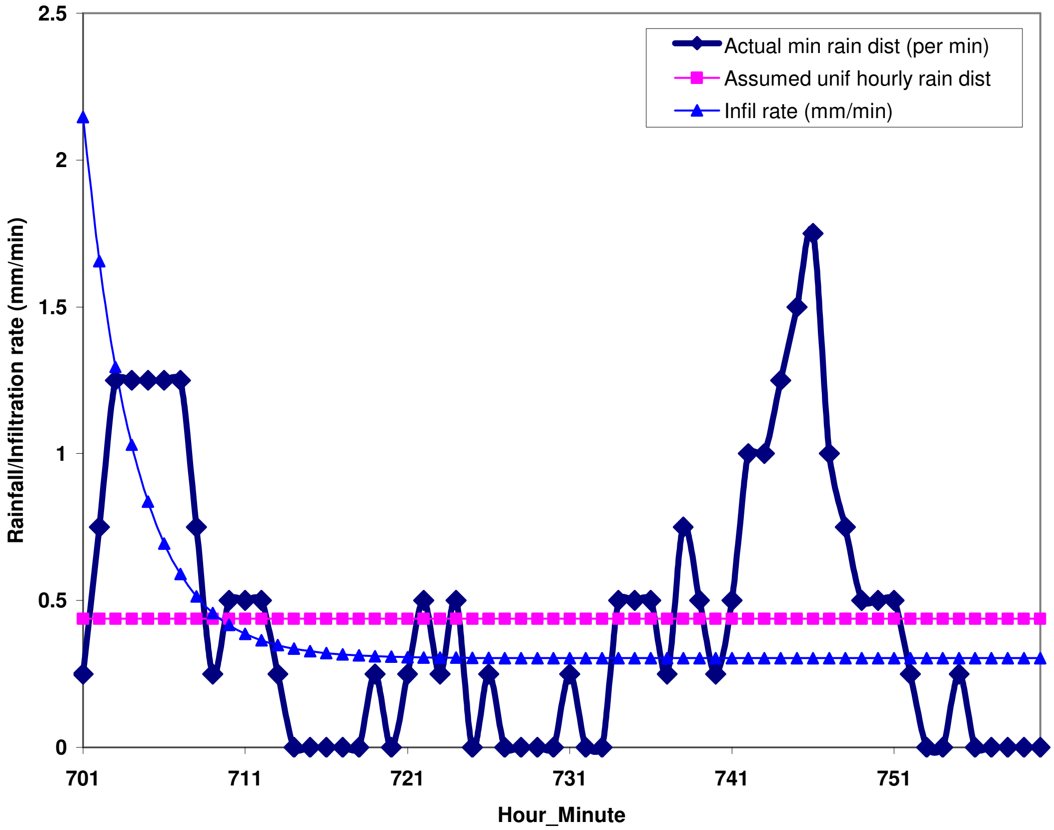


Figure 3-1. Comparison of infiltration and runoff for the actual and assumed uniform hourly rainfall rates (using data from LSU AgCenter Climate, 2004; Skaggs, 1980).

The primary objective of this study was to describe a methodology to be used to write and incorporate into DRAINMOD a five-minute rainfall time increment subroutine to be used whenever the amount of rainfall within any given hour is equal to or more than 0.2 cm. This was accomplished by modifying the hourly rainfall input data file to include five minute rainfall data collected at the USDA-ARS Ben Hur research site if the hourly rainfall was equal or more than 0.2 cm and describing a methodology for the five minute infiltration and runoff calculations subroutine. Also recommendations of future work to complete the writing and incorporation into DRAINMOD of the five-minute time increment subroutine are given.

3.2 Materials and Methods

3.2.1 Current DRAINMOD Model and the Desired Rainfall Intensity Changes

A general flow chart of the original DRAINMOD model, in which hourly rainfall data is used to calculate infiltration and runoff, is shown in Appendix A. The dotted lines indicate the sections of the original DRAINMOD model that needed to be modified. Figure 3-2 shows a general flow chart of the modifications to be made on the original DRAINMOD model, which would include a dynamic vertical saturated hydraulic conductivity (K_s) subroutine, a dynamic maximum surface depressional storage (STMAX) subroutine and a five-minute rainfall time increment subroutine algorithm (to be included later).

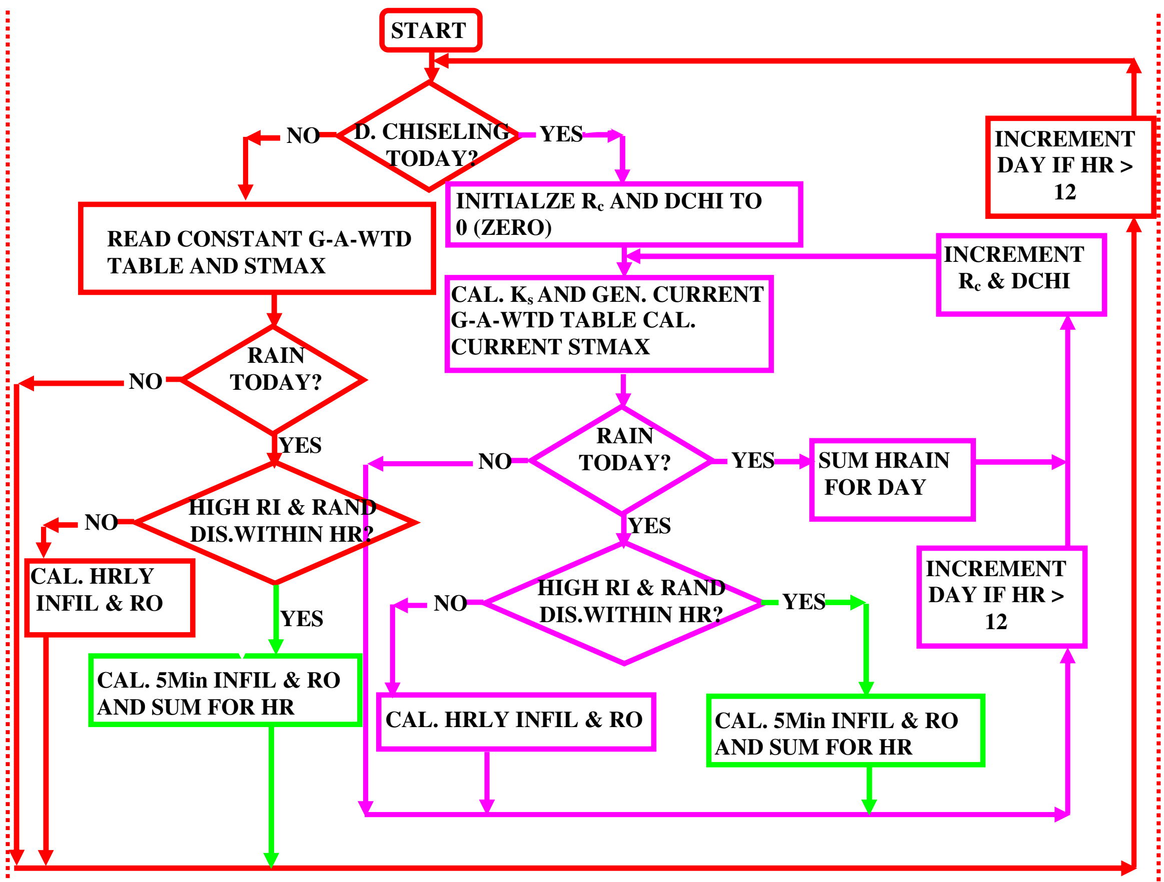


Figure 3-2. A general flow chart of DRAINMOD model modifications to be made

The algorithm for the five-minute rainfall time increment modification is discussed in the following section.

3.2.2 The Five-minute Rainfall Time Increment Algorithm

The first step in modifying the current DRAINMOD model to incorporate rainfall intensity is to modify the rainfall input data to include five-minute rainfall amounts if the hourly rainfall amount is equal to or greater than 0.2 cm. The next step is to generate the five-minute rainfall time increment algorithm to be used to generate the needed subroutine, which is then incorporated into the DRAINMOD model.

3.2.2.1 Modification of the Rainfall Input Data File (Filename.RAI)

According to Skaggs and Fernandez (1998) the rainfall-input data for the current DRAINMOD model is hourly amount in hundredths of an inch. An excerpt of this file is presented in Table 3-1. Each line of data contains the station ID in columns 1-6, the year in columns 8-11, and the month in columns 12-13. The remainder of the line contains the hourly rainfall amounts. These are specified as day (2 columns), hour (2 columns) and amount (4 columns) with all data right justified. There is a maximum of 12 Day-Hour-Rainfall values per line. A new line is started whenever the month changes.

One possible rainfall input data file modification would be to use five-minute rainfall amounts in hundredths of inches for all rainfall data. However, the rainfall data modification considered in this study was to use hourly rainfall amounts if hourly rainfall rates less than 0.2 cm/hr and five-minute amounts if and when the hourly rainfall amount is equal or greater than eight hundredths of an inch (0.2 cm) (combined rainfall rate approach). This modification was chosen because data collection at the USDA-ARS Ben Hur research site using CR7 datalogger was set up to collect five-minute rainfall amounts whenever the hourly rainfall amount was equal to or greater than 0.2 cm. Use of hourly rainfall amounts if hourly rainfall rates less than 0.2 cm/hr is sufficient in the modified DRAINMOD because runoff and hence infiltration measurement error is minimal. This combined rainfall rate approach has an added advantage of saving simulation computation time.

Table 3-1. Excerpt from the distribution disk file for hourly rainfall (Skaggs and Fernandez, 1998)

```
ID  YEAR M  D H  rf D H  rf D H  rf D H  rf D H  rf D H  rf D H  rf D H  rf D H  rf D H  rf D H  rf D H  rf
319476 1959 1  114   9 115   2 116   2 117   3 118  16 119  22 120   4 123   1 124   4 2 1   5 2 2   3 2 3   1
319476 1959 1  2 4   2 816   6 817   6 818   5 819   8 820   1 821   5 822   1 824   116 8   116 9   11611   5
319476 1959 1 1612   31613   11614   422 2  6722 3  1322 4  1222 5   82811   12812   12813   331 2   131
3   1
319476 1959 1 31 4   231 5   131 6   131 7   131 8   1
319476 1959 2  3 8   4 3 9   3 310   5 311   7 312   5 313   3 314   2 315   1 318   1 319   2 4 1   1 4 2   3
319476 1959 2  4 3   3 4 6   4 4 7   4 4 8   2 4 9   1 410   4 411  11 412  24 413  45 414  38 415  27 416  10
319476 1959 2  417  16 418  14 419  10 420   4 421  10 422   2 424   1 5 1   1 9 3   1 9 8   1 9 9   1 910   2
319476 1959 2 1223   11224   313 1   513 2   313 3   913 4   613 5   613 6  1013 7   513 8  1913 9   41410
2
319476 1959 2 1411   115 7   215 8   215 9   118 7   118 8   118 9   223 6   123 7   423 8   823 9   72310   6
319476 1959 2 2311   12524   226 1  1126 2  1226 3   326 4   226 8   226 9   12824   1
319476 1959 3  1 3   1 1 7   1 1 8   1 110   1 111   1 124   4 2 1   4 2 2   7 2 3  10 2 4  11 2 5   4 2 6   3
319476 1959 3  2 7  17 2 8  12 2 9  10 210   8 211   8 212   4 213   3 214   2 215   1 321  10 322   6 323   4
319476 1959 3  324   3 523   2 524  13 6 1  23 6 2  45 6 3  24 6 4  15 6 5   8 6 8   2 6 9   11018   21124   4
319476 1959 3 12 2   112 3   112 4   112 7   112 8  1612 9   115 7   215 8   31510   71511  111512   221 3
12
```

* M is month, D is day of the month, H is hour and rf is rainfall in hundredths of inches.

In this modified rainfall input data file, hourly rainfall amounts are located at the top and the five-minute rainfall amounts if the hourly rainfall amount is equal or less than eight hundredths of inches at the bottom. Keywords HRY (hourly) and FVM (five-minute) within the same rainfall input data file are used to separate the two time increments. Table 3-2 is an example using the same data (Skaggs and Fernandez, 1998) used in Table 3-1.

Table 3-2. An example of the combined hourly and five-minute rainfall file

```
HRY   ***** Hourly Rainfall Amounts
ID  YEAR M  D H  rf D H  rf D H  rf D H  rf D H  rf D H  rf D H  rf D H  rf D H  rf D H  rf D H  rf D H  rf
319476 1959 1  114   9 115   2 116   2 117   3 118  16 119  22 120   4 123   1 124   4 2 1   5 2 2   3 2 3   1
319476 1959 1  2 4   2 816   6 817   6 818   5 819   8 820   1 821   5 822   1 824   116 8   116 9   11611   5
319476 1959 1 1612   31613   11614   422 2  6722 3  1322 4  1222 5   82811   12812   12813   331 2   131 3   1
319476 1959 1 31 4   231 5   131 6   131 7   131 8   1
319476 1959 2  3 8   4 3 9   3 310   5 311   7 312   5 313   3 314   2 315   1 318   1 319   2 4 1   1 4 2   3
319476 1959 2  4 3   3 4 6   4 4 7   4 4 8   2 4 9   1 410   4 411  11 412  24 413  45 414  38 415  27 416  10
319476 1959 2  417  16 418  14 419  10 420   4 421  10 422   2 424   1 5 1   1 9 3   1 9 8   1 9 9   1 910   2
319476 1959 2 1223   11224   313 1   513 2   313 3   913 4   613 5   613 6  1013 7   513 8  1913 9   41410   2
319476 1959 2 1411   115 7   215 8   215 9   118 7   118 8   118 9   223 6   123 7   423 8   823 9   72310   6
319476 1959 2 2311   12524   226 1  1126 2  1226 3   326 4   226 8   226 9   12824   1
319476 1959 3  1 3   1 1 7   1 1 8   1 110   1 111   1 124   4 2 1   4 2 2   7 2 3  10 2 4  11 2 5   4 2 6   3
319476 1959 3  2 7  17 2 8  12 2 9  10 210   8 211   8 212   4 213   3 214   2 215   1 321  10 322   6 323   4
319476 1959 3  324   3 523   2 524  13 6 1  23 6 2  45 6 3  24 6 4  15 6 5   8 6 8   2 6 9   11018   21124   4
319476 1959 3 12 2   112 3   112 4   112 7   112 8  1612 9   115 7   215 8   31510   71511  111512   221 3  12
FVM   ***** Five Minute  Rainfall Amounts
ID  YEAR M  D H F rf D H F  rf D H F  rf D H F  rf D H F  rf D H F rf D H F  rf D H F  rf D H F  rf D H F  rf D H F  rf D H F  rf
319476 1959 1   1141    1 1142    2 1143    1 1144    1 1145  0 1146  0 1147    0 1148    1 1149    1 11410  1  11411 1
11412 0
```

* M is month, D is day of the month, H is hour, F is five-minute interval and rf is rainfall in hundredths of inches.

Each line of hourly rainfall data is formatted as described by Skaggs and Fernandez (1998). Each line in the five-minute rainfall amount portion contains the station ID in columns 1-6, the year in columns 8-11, and the month in columns 12-13. The remainder of the line contains the hourly rainfall amounts. These are specified as day (2 columns), hour (2 columns) five-minute interval, F (2 columns) and amount in hundredths of an inch (4 columns) with all data right justified. There is a maximum of 12 D-H-F-rf values per line for the sixty minutes of the hour.

3.2.2.2 Five-minute Subroutine Algorithm

In the current DRAINMOD model calculation of infiltration using hourly rainfall (subroutine RAINDA), an iteration process is used with Equation 3-1 to determine the cumulative infiltration (F) at the end of hourly time intervals.

$$f = A/F + B \tag{3-1}$$

where $A = K_s M S_{av}$ (cm^2/hr) and $B = K_s$ (cm/hr) are the Green-Ampt parameters, which depend on the soil properties (K_s), initial water content (M) and distribution (S_{av}) and surface conditions such as cover and crusting, which affect K_s. When the rainfall rate exceeds the infiltration capacity (f) given by Equation 3-1, Equation 3-2 is applied to conduct a water balance at the surface for time increments of three minutes to capture the distribution of infiltration, surface depression storage and surface runoff components.

$$P = F + \Delta S + RO \qquad (3\text{-}2)$$

where P is the rainfall or surface irrigation (cm), F is infiltration (cm), ΔS is the change in volume of water stored on the soil surface (cm), and RO is runoff (cm) during time Δt. Excess rainfall fills the surface depressions to a maximum depth (STMAX) for a given field after which additional water is apportioned to surface runoff. At the end of every hour, infiltration, surface runoff and the current depth of surface storage are accumulated to give the predictions of these components hourly.

Infiltration is accumulated hourly and used in Equation 3-1 until rainfall stops and all water stored in the surface depressions has infiltrated. Similarly the same values of parameters A and B are used as long as the rainfall event lasts, with an exception when the water table rises to the ground surface, in which case A is set to A = 0, and B is set equal to the sum of the drainage (D), ET and deep seepage rates shown in Equation 3-3 and illustrated by Figure 3-3 (Skaggs, 1980).

$$\Delta V_a = D + ET + DS - F \qquad (3\text{-}3)$$

where ΔV_a is the change in the air volume (cm), D is the lateral drainage (cm) from (or subirrigation into) the section, ET is evapotranspiration (cm), DS is the deep seepage (cm), and F is infiltration entering the section in time increment Δt. An infiltration event is assumed to terminate and new values of A and B evaluated for succeeding rainfall events at least two hours (arbitrary selected) after a rainfall event and/or without surface water for infiltration (Skaggs, 1980).

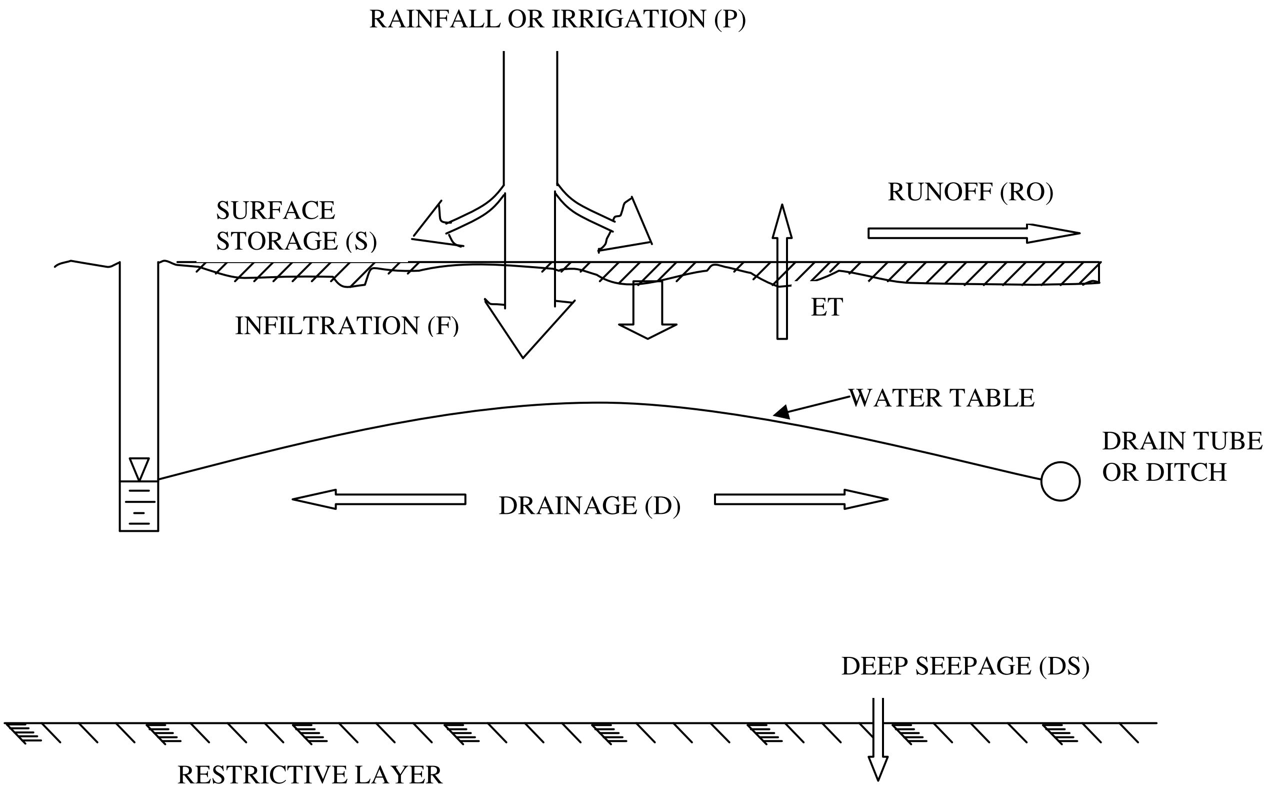


Figure 3-3. Schematic of water management system with drainage to ditches or drain tubes. Components considered in the water balance are shown in the diagram (Skaggs, 1980).

In the rainfall intensity modified DRAINMOD model, an additional subroutine algorithm (RAINDAI) to calculate infiltration using five-minute rainfall when hourly rainfall is ≥ 0.2 cm will be incorporated. The first step is to read the hourly rainfall amount. If the hourly rainfall amount is less than eight hundredths of an inch (0.2 cm), the original DRAINMOD model subroutine RAINDA is used. However, if the hourly rainfall is equal or greater than 2 cm, then the new five-minute rainfall infiltration calculation subroutine (RAINDAI) is used. For the subroutine RAINDAI algorithm, an iteration process is used with Equation 3-1 to determine the cumulative infiltration (F) at the end of five-minute time intervals. When the rainfall rate exceeds the infiltration capacity (f) given by Equation 3-1, Equation 3-2 is applied to conduct a water balance at the surface for time increments of one minute to determine the distribution of precipitation as infiltration, surface depression storage and runoff within the five minute period. Short time iterations increase the accuracy of DRAINMOD component predictions.

The excess rainfall fills the surface depressions to a maximum depth (STMAX) regardless of constant or time varying STMAX for a given field after which additional water is apportioned to surface runoff. At the end of every five-minute interval, infiltration and surface runoff are accumulated and the current depth of surface storage read to give the predictions of these components at five-minute time intervals. Also at the end of every hour, the twelve (12) five-minute time interval infiltration and surface runoff predictions are accumulated and the current depth of surface storage read to give the predictions of these components hourly as before. Infiltration is accumulated every five-minute time intervals and hourly and used in Equation 3-1 until rainfall stops and all water stored in the surface depressions has infiltrated as explained above. Therefore, the rainfall intensity (RI) modified DRAINMOD model (DRAINMOD-RI) can be used with or without additional changes to DRAINMOD subroutines such as STMAX and vertical saturated hydraulic conductivity (K_s). The algorithm for the five-minute rainfall time increment is shown in Figure 3-4 and part of the code is given in Appendix B.

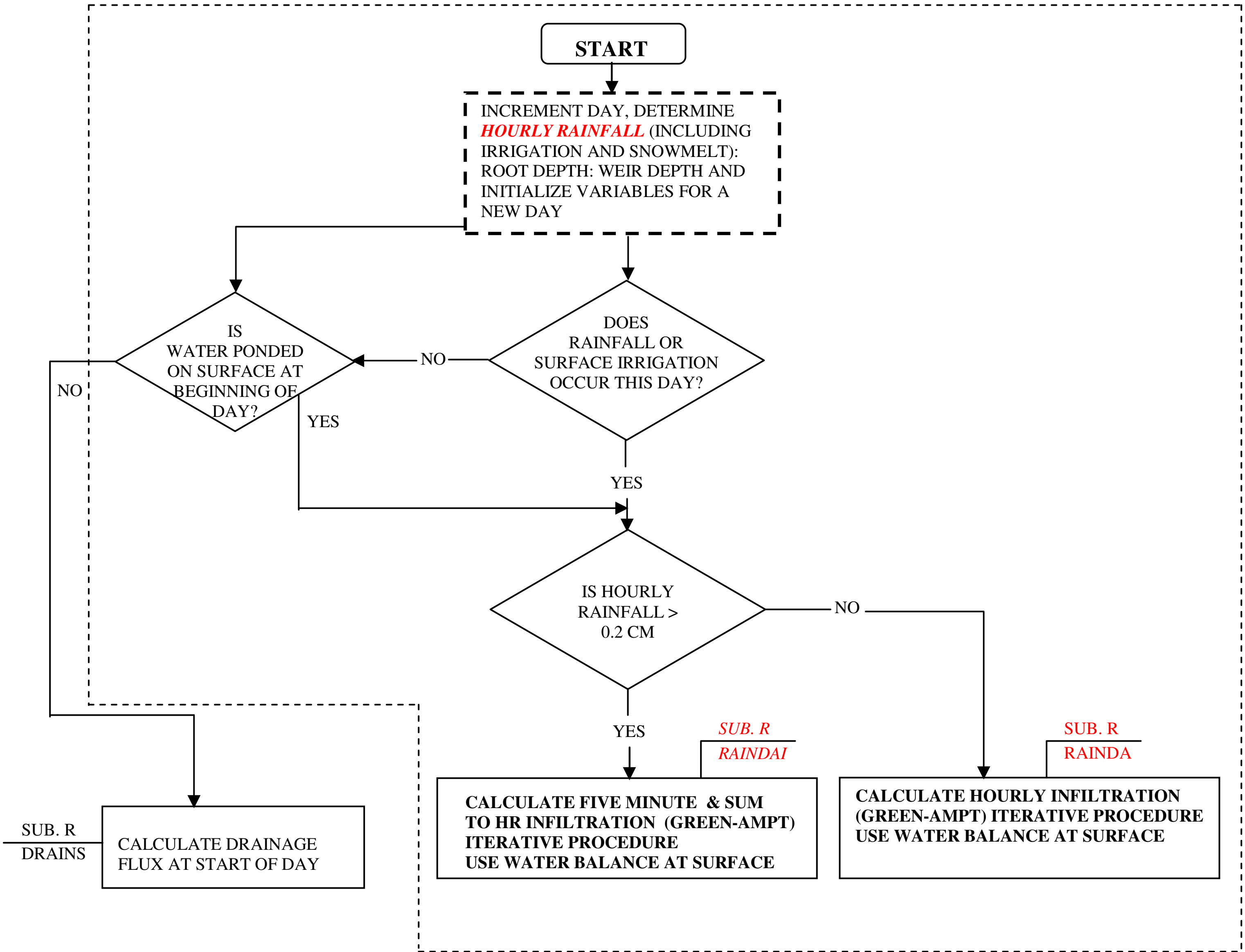


Figure 3-4. An abbreviated flow chart for the five-minute time increment subroutine within DRAINMOD

3.3 Conclusion and Recommendations

Rainfall intensity (RI) is one of the major factors that affect infiltration and surface runoff (Skaggs, 1980) because if rainfall intensity is greater than the infiltration rate, water will accumulate on the surface, and runoff will occur. In this study a methodology for using a five-minute rainfall time increment subroutine within

DRAINMOD was described in order to incorporate rainfall intensity factor in the calculation of infiltration and surface runoff and hence improve the prediction of these components by the DRAINMOD model. However, this study is far from complete.

Future work could include using the algorithm described in the methodology to write a five-minute rainfall time increment (RI) subroutine using Microsoft FORTRAN PowerStation version 4.0 (Microsoft, 1995) and incorporating it into the current DRAINMOD model. The RI modified DRAINMOD model (DRAINMOD-RI model) could then be validated using the surface runoff data from the USDA-ARS Benhur Research site measured between 1995 and 2001.

CHAPTER FOUR

VARIATION OF VERTICAL SATURATED HYDRAULIC CONDUCTIVITY WITH RESPECT TO CUMULATIVE RAINFALL AFTER DEEP CHISELING A SOUTHERN ALLUVIAL SOIL

4.1 Introduction

For the Commerce silt loam soil [fine silty, mixed, non-acid, thermic Aeric Flivaquent], a southern Louisiana alluvial soil, the top layer is the least hydraulically conductive (Rogers et al., 1991) due to the formation of soil surface seal (Martinez-Gamino, 1994). Saturated hydraulic conductivity for the Commerce silt loam soil increases with depth from 1.46 cm/hr (0.6 m deep) to 4.39 cm/hr (1.5 m deep) and then decreases with depth to 2.88 cm/hr (2.4 m deep) as measured by Rogers et al. (1991). A tillage practice that has been used in Louisiana to break the soil surface crust and the hard pan in order to increase infiltration and reduce surface runoff is deep chiseling (Bengtson et al., 1995). Deep chiseling used to be a common practice in the Lower Mississippi River Valley (LMRV) but in more recent years farmers have moved away from it because they did not see any economic benefits and because minimum tillage has been widely adopted in the last ten years (Grigg and Fouss, 2002). However, deep chiseling is still needed in this region when subsurface drainage is used.

In the previous research (Bengtson et al., 1995) when deep chiseling was carried out every one year to two years [with data collection beginning right after deep chiseling] subsurface drainage systems decreased runoff. However, research by Grigg et al. (2003) from 1995 to 1996 on fields with subsurface drainage, whose measurements were taken 3 to 5 months after deep chiseling, showed that subsurface drainage did not reduce surface runoff. Grigg et al. (2003) planted the plots 3 to 5 months after deep chiseling the soil.

Deep chiseling on Grigg et al.’s (2003) fields was done in the late fall while measurements were taken beginning after planting corn and applying crop nutrients and pesticides in late March 1996 and in late April 1997. However, because of the large amount of rainfall in Louisiana (Bengtson and Carter, 2004) the top clay loam soil aggregates are broken into fine particles which cause sealing (Martinez-Gamino, 1994) that diminished the benefits of deep chiseling by the time measurements were taken by Grigg et al. (2003). This may explain the difference between Bengtson et al.’s (1995) and Grigg et al.’s (2003) contradicting results. According to the results by Grigg et al. (2003), deep chiseling [just before the growing season] may be necessary if subsurface drainage is to reduce nutrient loss in surface runoff from the Commerce silt loam soil, which is representative of large areas in the LMRV region (Fouss and Willis, 1990).

Deep chiseling increases infiltration and reduces surface runoff by increasing the vertical component of saturated hydraulic conductivity (K) of the top layer and adjacent layers of soil (Kincaid, 2002). Unfortunately, the benefits of deep chiseling in increasing K and hence infiltration are only temporary because the soil surface seal (Martinez-Gamino, 1994; Slattery and Bryan, 1994; Assouline and Mualem, 2002) and soil compaction increases gradually as fine particles fill the soil pore spaces after subsequent rainfall events (Freebairn et al., 1991; Rao et al, 1998; Allen and Musick, 2001). The gradual increase in soil surface seal formation and soil compaction over time causes a gradual decrease in K (Kincaid, 2002). Information on the variation of K with the amount of rainfall over time after deep chiseling can be used to make agricultural management decisions. Often hydrologic models such as DRAINMOD help make these predictions.

DRAINMOD, a computer hydrologic model, was developed at North Carolina State University in the late 1970s (Skaggs, 1978). This model is based on the water balance in the soil profile and uses long-term (20 to 40 years) climatological records to simulate the performance of drainage and water table control systems on a continuous basis. DRAINMOD predicts surface runoff, water table depth, drainage outflow, soil water content, evapotranspiration (ET) and infiltration on hourly, daily, monthly or annual basis in response to given soil properties, crop variables, climatological data, and site parameter inputs. However, DRAINMOD does not accurately predict infiltration and runoff for the crusting prone alluvial soils of Louisiana. One of the possible reasons for this inaccurate prediction is that K_s, taken by Skaggs (1980) as 1/3 of measured field saturated hydraulic conductivity (K) due to entrapped air (Reynolds and Elrick, 1986), and which affects the infiltration and runoff processes, is assumed constant in the current DRAINMOD model irrespective of the soil condition. Vertical saturated hydraulic conductivity depends on tillage operations, climatic conditions and soil cover among other factors (Skaggs, 1980).

Because the prediction of infiltration and runoff by the Green-Ampt equation in DRAINMOD is most sensitive to errors in K_s (Skaggs, 1980), the current work focuses on measuring and using the current K_s after deep chiseling a soil. Information gained from DRAINMOD model simulations will aid engineers and farmers to determine how often to deep chisel farm fields depending on the type of soil for specific climatic conditions. Improved predictions will help farm managers make better decisions.

Measurement of saturated hydraulic conductivity of soil in the field is accomplished using different methods, which often have different operating ranges, flow geometries, boundary conditions, sample sizes, and underlying assumptions.

Some of the field methods used to measure vertical saturated hydraulic conductivity (K) include the single and double ring infiltrometers (Bouwer, 1986), double tube test (Bouwer, 1961), air-entry permeameter (Amoozegar and Warrick, 1986), and borehole permeameter (ASTM Standards, 1998). Some empirical equations that have been used to estimate K from soil particle size distribution include Hazen (1892), Krumbein and Monk (1942), Harleman et al.(1963), Masch and Denny (1966), Kozeny-Carman (in Bear, 1972), Alyamani and Sen (1993), Kolterman and Gorelick (1995), Arya et al. (1999), and Boadu (2000).A summary description of these methods and their advantages and limitations is given in chapter two section 2.9.

Selecting a suitable method for particular soil and site conditions is important in obtaining representative estimates of K. A faster and accurate method was needed to determine representative vertical saturated hydraulic conductivity of the alluvial soils in Louisiana and the rest of the Lower Mississippi River Valley region.

4.2 Materials and Methods

The double ring infiltometer method (Bouwer, 1986) was selected because it is relatively accurate and yet it is less labor intensive compared to other methods. In this study, K for the top layer of the Commerce silt loam was measured after each rainfall event to determine the variation of K depending on the cumulative rainfall after deep chiseling some of the sixteen USDA-ARS Ben Hur Research Site plots.

4.2.1 Field Site Description

This study was conducted on a Commerce silt loam soil at the USDA-ARS Ben Hur Research Field Site located 5km south of Baton Rouge, Louisiana. The soil properties of Commerce silt loam are given in Table 4-1. The site was composed of 16 (0.2 ha) bordered field plots (Figure 4-1) equipped with shallow and deep subsurface drains, surface ditches, sumps, and instrumentation for automated water table management and sampling of surface and subsurface drain effluent (Fouss and Willis, 1990). Each plot, 35 m by 61 m, is separated from the other plots or the surrounding areas using a 0.3 m high berm coupled with a vertical border 1.7 m deep made of 6-mil polyethylene plastic film beginning from 0.3 m below the ground surface, to permit cultivation (Fouss and Willis, 1990). Three subsurface drain lines were installed in each plot at a depth of 1.0 m below the ground surface and spaced 15 m apart. The middle drain was used as the experimental drain line while the two outer drain lines were used as the buffer drains. The area centered over the middle line and 7.5 m on either side of the middle drain line or 0.1 ha was used as the controlled experimental area (Fouss and Willis, 1990).

The ground surface of all plots was precision leveled to a compound slope of 0.2% cross slope and to 0.2% slope in the direction of the subsurface drainage flow (Fouss and Willis, 1990). According to Fouss and Willis (1990), surface runoff was collected in a shallow ditch before being routed through an H-flume at the down-slope end of each plot. Willis et al. (1991) gives a detailed description of the experimental design and field instrumentation.

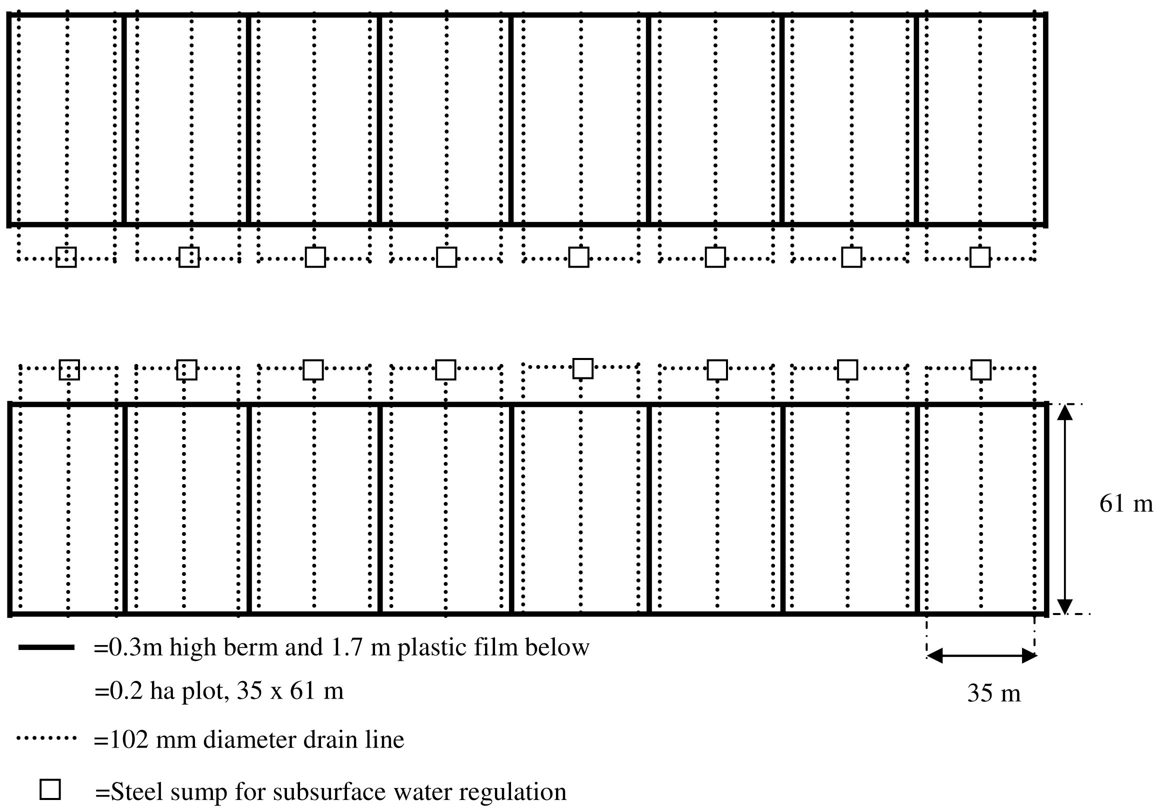


Figure 4-1. Schematic layout of the Ben Hur Field Site located 5 miles south of Baton Rouge, Louisiana. Construction site was completed in 1993 and data collection began in 1995 (modified from Grigg et al., 2003)

Table 4-1. Soil properties for Commerce silt loam at Ben Hur Field Site (from Kornecki and Fouss, 2001).

Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Soil Type Classification
0-28	36.0	37.0	27.0	Clay loam
28-74	50.0	36.5	13.5	Silt loam
74-153	50.0	39.5	10.5	Loam

The initial water management treatments evaluated in these plots were: surface drainage only (SUR), conventional drainage at a depth of 1 m (CD), controlled water table at 45 ± 5 cm depth, and 75 ± 5 cm depth (Fouss and Willis, 1990). However, analysis of these treatments by Grigg et al. (2003) for the year 1995-1996 showed that subsurface drainage, measured 3 to 5 months after deep chiseling, did not significantly reduce surface runoff. These results were in contrast to the results by Bengtson et al. (1995) who reported that subsurface drainage reduced surface runoff, with the only difference being that Bengtson et al. (1995) deep chiseled their fields and began collecting data right after deep chiseling, which may explain the difference (Grigg et al., 2003). This led to changes in the treatments at the research site by Grigg and Fouss (2002) as explained below.

Currently there are four treatments with four replications each (Grigg and Fouss, 2002). The plots with the first three treatments, namely surface drainage only, shallow-installed (0.6 m deep) drainage and deep-installed (1.0 m deep) and controlled drainage, were all deep-chiseled. The fourth treatment has deep-installed and controlled drainage but without deep-chiseling to test how deep chisel plowing affects surface runoff and nutrient movement in the Lower Mississippi River Valley (Grigg and Fouss, 2002). Two deep drained (1.0 m deep) plots were used for this research, one of which was deep chiseled and the other non-deep chiseled (control).

4.2.2 Deep Chiseling and Other Field Operations

Normally deep chiseling is performed in the fall and followed by one or more secondary tillage operations in the spring. The fall operation cuts and incorporates some of the residue, making it more susceptible to decomposition and winter weathering than undisturbed residue. This partially decomposed residue is easily broken up and covered by secondary tillage operations such as disking to make the seed bed ready for planting.

Deep chisel plowing, using John Deere 915 V-Ripper with shanks (blades) 0.45 m deep at a spacing of 0.75m (Figure 4-2), was done on February 3rd 2003. Ten days after deep chiseling, the distance of each strip from one end of the field was measured and recorded to help determine these locations after a second tillage operation was done. Two metal pins, one on either side of the field and perpendicular to each other, were driven into the ground and a 61m long measuring tape was tied to the top of each metal pin. The distance from one as a reference end point to each strip was measured and recorded.

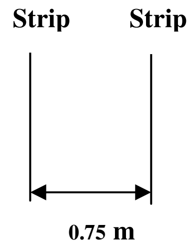


Figure 4-2. Schematic of John Deere 915 Ripper spacing, shanks are 75cm apart.

The first secondary operation, disking, was done on March 21st 2003 a few days after a rain event, which softened the large clods. A second disking was done on March 24th 2003 followed by rolling to break the large clods because of lack of rainfall in readiness for planting. Finally corn was planted on March 25th 2003 immediately following the rolling operation after which pre-emergent herbicide was applied. A possible negative impact of these secondary operations is additional compaction, which may further reduce the benefits of deep chiseling by reducing water infiltration into the soil.

4.2.3 Installation of Double-ring Infiltrometers

The double-ring infiltrometers (Figure 4-3) were made from 30cm and 20cm inside diameter green PVC sewer pipes (Coburn Supply Co., Baton Rouge, Louisiana). Both the inner and the outer rings were cut 30 cm in height. A total of 21 double-ring infiltrometers were made and used in the field determination of vertical saturated hydraulic conductivity.

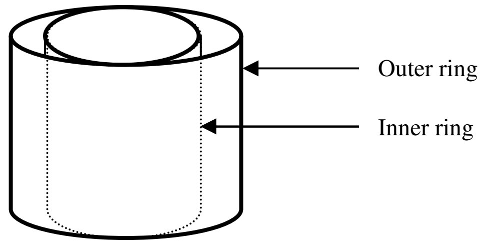


Figure 4-3. Schematic of double-ring infiltrometer, made from sewer pipe (Coburn Supply Co., Baton Rouge, Louisiana)

The 21 double-ring infiltrometer locations were marked on March 25th 2003 right after corn planting as shown by the schematic of the plot layouts in Figure 4-4. In Figure 4-4 the two plots are drawn with space between them for clarity but in reality they are side by side. The spacing between the strips was 10.4 m apart and the locations within each strip were 15.2 m apart. The double-ring infiltrometers were then concentrically driven 10cm into the soil using a 25 x 25cm soil packer. Meter rulers were then installed vertically against the inner ring wall to measure the rate of decrease of water level in the inner ring. A reference point on the ruler was marked and recorded.

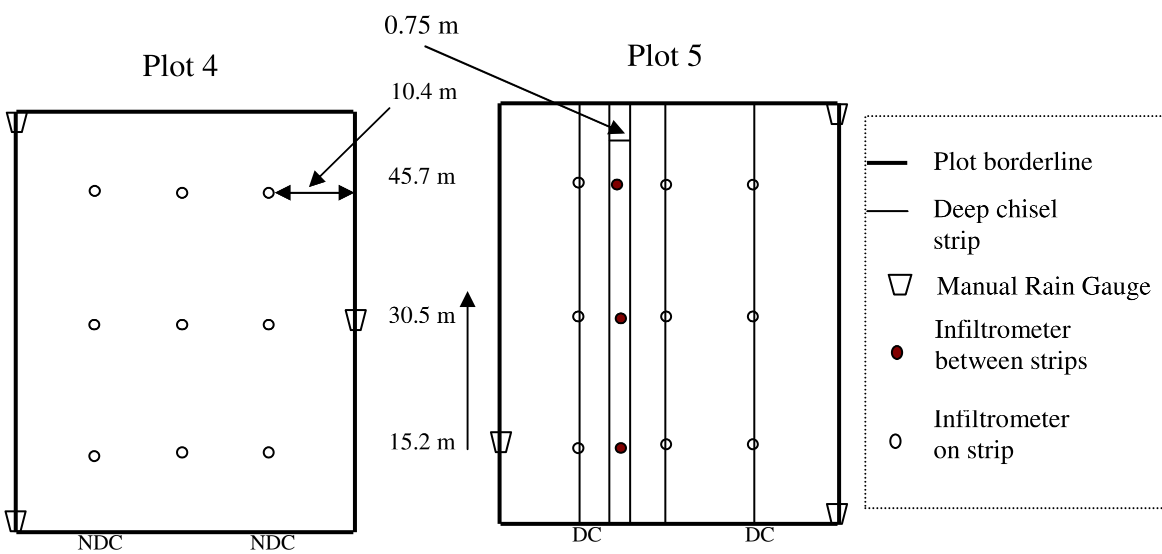


Figure 4-4. Schematic of field layout and measurement locations

Experimental design comprised two treatments; one deep chiseled plot (DC) and a control plot that was not deep chiseled (NDC). Nine readings of vertical hydraulic conductivity were taken from three locations per strip for three different strips in the deep chiseled field. The same number of measurements was taken from the control field. Three extra measurements were taken between the strips (Figure 4-5) on the chiseled field only to determine if there was a difference between vertical saturated hydraulic conductivity (K) on and between the strips. It was hypothesized that there was no difference between the measured K on and between the strips because the shanks are tapered so that they can break the hard pan underneath two adjacent strips.

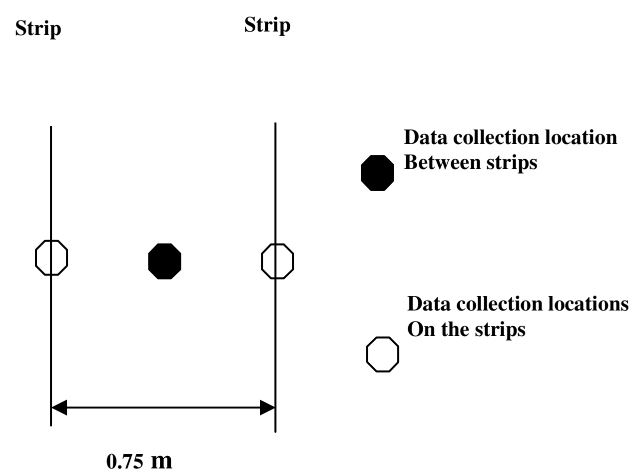


Figure 4-5. K_s data collection locations on and between deep chiseled strips

4.2.4 Field Measurements

4.2.4.1 Rainfall

Rainfall data was needed to determine how soil vertical saturated hydraulic conductivity (K) measurements varied with amount of rainfall over time (cumulative rainfall). Six model 00850GT 127mm manual rain gauges manufactured by Chaney Instrument Company were installed throughout the two experimental plots to check the rainfall variability during a rain event. Tipping bucket rain gauges had been previously installed; two model TE525 rain gauges manufactured by Campbell Scientific, Inc. and two model 2149 manufactured by American SIGMA whose data is electronically collected by the data loggers and stored in a personal computer (PC). If there were no significant differences in the rainfall amounts in all the rain gauges on the two plots used, the average rainfall value was used for the purpose of this research (Table 4-2).

Another source of rainfall for a nearby weather station in the same location was the Louisiana Agriclimatic Information web site (LSU AgCenter Climate, 2004). This was recorded as a check for the rainfall data at the research site. Table 4-2 shows amount of rainfall (mm) for each of the six manual (M) and two electronic (E) rain gauges at the research site, the average amount of rainfall for the research area rain gauges (AV), the rainfall from the adjacent weather station (W) and the average cumulative rainfall (AVC) during the field experiment period. Cumulative rainfall after deep chiseling (February 3rd 2003) but prior to the field vertical saturated hydraulic conductivity measurements (April 2nd 2004) was 247 mm. This cumulative rainfall was used to extrapolate the vertical saturated hydraulic conductivity (K) trends to determine K on the day deep chiseling was done.

4.2.4.2 Water Table Depth, Volumetric Moisture Content and Soil Bulk Density Measurement

Water table depth (WTD) measurements were taken to find if there was a relationship between water depth and volumetric moisture content between 5 and 10 cm below the ground surface. The average volumetric moisture content (VMC) and soil bulk density (BD) for the deep chiseled and not deep chiseled plots were measured to determine differences. Finally, the WTD and VMC measurements were used to find if water table depth or initial volumetric moisture content had an effect on the measured vertical saturated hydraulic conductivity (Table 4-3).

Table 4-2. A record of the amount of rainfall for each rain gauge, the average rainfall, weather station next to the plots, and the average cumulative rainfall on the research plots. M = manual rain gauge, E = electronic rain gauge, AV = average rainfall, W = rainfall from weather station near the research plots, AVC =average cumulative rainfall on the research area. -- indicates missing data (average of available data was used). All readings are in mm.

Date	M1	M2	M3	M4	M5	M6	E1	E2	AV	W	AVC
4/02/03[α]	**--**	**--**	**--**	**--**	**--**	**--**	**0**	**0**	**0**	**0**	**0**
4/09/03	**--**	**--**	**--**	**--**	**--**	**--**	**122**	**124**	**123**	**120**	**123**
5/21/03	10	11	10	11	10	12	11	10	11	9	134
5/26/03	**4**	**5**	**4**	**4**	**5**	**5**	**3**	**4**	**4**	**3**	**138**
6/02/03	5	5	5	5	5	5	5	5	5	6	143
6/03/03	3	3	3	3	3	3	2	2	2	3	145
6/5-6/03	**8**	**9**	**8**	**8**	**8**	**8**	**7**	**7**	**8**	**6**	**152**
6/11/03	20	20	22	20	19	20	21	21	20	18	173
6/17/03	44	47	47	45	44	48	50	47	47	37	220
6/18/03	6	8	8	8	7	8	0	0	5	10	224
6/19/03	**5**	**6**	**5**	**5**	**5**	**6**	**4**	**4**	**5**	**3**	**229**
6/23/03	5	5	6	5	6	6	7	8	6	8	235
6/25/03	**9**	**10**	**10**	**10**	**10**	**10**	**9**	**9**	**10**	**9**	**245**
6/27/03	4	4	4	4	5	4	4	6	4	3	249
7/01/03	**38**	**38**	**38**	**41**	**39**	**36**	**35**	**37**	**38**	**36**	**286**
7/07/03	23	24	24	25	23	22	22	23	23	18	309
7/14/03	28	26	28	26	25	26	28	--	24	20	336
7/18/03	18	18	18	18	18	18	20	26	19	14	357
8/13/03	**107**	**104**	**107**	**89**	**102**	**102**	**112**	**123**	**106**	**97**	**466**
8/22/03	41	38	42	36	38	41	56	55	43	34	514
9/02/03	41	41	43	38	41	42	44	42	41	39	556
9/19/03	56	53	58	53	56	58	71	70	59	53	619
9/22/03	**28**	**28**	**29**	**27**	**28**	**28**	**26**	**24**	**27**	**24**	**645**
10/14/03	48	53	51	53	51	48	53	54	51	53	697

[α] Bold data shows amount of rainfall on K measurement dates

The average ground surface elevation in the middle of each precision-leveled plot (599.54 cm and 598.32 cm for plots 4 and 5 respectively) from a known reference point was used as the reference for the electronic measurement of water table depths on the middle drain line. This was achieved by using a float-sensor in the outlet riser, located inside the sump, and data was continuously collected by CR7 Campbell Scientific data-loggers and stored in personal computers (PCs).

The soil core samples were collected about 5 cm from each measurement location at a depth between 5 and 10 cm for soil water content analysis at the time of measurements of vertical saturated hydraulic conductivity. An AMS Soil Recovery Probe enhanced with a slide hammer (Art's Manufacturing and Supply Inc., American Falls, Idaho) was used to collect the core samples. This probe collected the samples in plastic liners, 2.2-cm inner diameter. The probe was advanced 10 cm into the soil using a slide hammer. The core samples were kept in coolers to minimize moisture loss through evaporation. The volumetric water content and the soil bulk density for the soil core samples were determined by cutting 4 cm long cores from between 5 and 10 cm depth from the ground surface and oven drying at 105^{o}C for at least 24 hours.

Table 4-3. Water table depth (WTD), average volumetric moisture content (VMC) and average soil bulk density (BD) of samples at 5-10 cm depth for the non-deep chiseled and deep chiseled plots.

Date	Non-deep chiseled plot			Deep chiseled plot		
	WTD (cm)	VMC (%)	BD (gcm^{-3})	WTD (cm)	VMC (%)	BD (gcm^{-3})
4/02/03	-67.54	38	1.61	-76.72	40	1.61
4/10/03	-28.54	41	1.62	-26.22	42	1.55
5/29/03	-118.14	32	1.78	-115.72	35	1.76
6/09/03	-135.74	31	1.72	-135.92	37	1.80
6/19/03	-135.44	39	1.75	-135.82	40	1.63
6/25/04	-135.84	37	1.65	-138.02	36	1.65
7/02/03	-115.44	38	1.67	-118.92	38	1.62
8/13/03	-81.74	40	1.67	-64.62	40	1.64
10/02/03	-71.14	33	1.75	-79.02	35	1.71

4.2.4.3 Vertical Saturated Hydraulic Conductivity Measurement

The first K measurements were carried out one day after installation of double-ring infiltrometers during which time cumulative rainfall since deep chiseling was initialized as zero (0). This was done to determine how K varied depending on cumulative rainfall after deep chiseling plot 5. Subsequent measurements were taken a day after a significant rainfall event until the average K for the deep chiseled plot was not significantly different from K for the plot that was not deep chiseled (plot 4). It is important to note that for correlation purposes, rainfall for each event was recorded and added to the previous cumulative rainfall prior to K measurements.

During the measurements both the inner and outer rings were open to the atmosphere, assuming that water evaporation rate into the atmosphere is negligible compared to the infiltration rate. Falling head tests were used to determine vertical saturated hydraulic conductivity for the top layer of the Commerce silt loam soil. Water was gently added into the outer ring first (Test method D 5126 of ASTM Standards (1998)) to act as a barrier to the lateral movement of water from the inner ring (Figure 4-3).

The inner ring was then filled with water quickly but gently to avoid erroneous measurements and the flow rate was measured directly from the rate of the decline in the water level inside the inner ring. The experiment was continued for about four hours after which time the rate of the decline of water level in the inner ring had approximately stabilized (Figure 4-6). The outer ring was kept filled with water during the experiments.

The head difference over a given time for the later (steady state) portion of the tests was used to calculate vertical saturated hydraulic conductivity (Table 4-4). Also recorded and compared was the vertical saturated hydraulic conductivity on the strips and between the strips (Table 4-5).

Table 4-4. Average (AV) vertical saturated hydraulic conductivity for the non-deep chiseled and deep chiseled plots (AV = Average, Std = Standard deviation, Max = Maximum, Min = Minimum measured values).

Date	K ($cmhr^{-1}$) – Non deep chiseled plot				K ($cmhr^{-1}$) – Deep chiseled plot			
	AV	Std	Max	Min	AV	Std	Max	Min
4/02/03[γ]	**0.63**	**0.86**	**2.70**	**0.08**	**2.64**	**2.46**	**7.00**	**0.17**
4/10/03	0.21	0.26	0.84	0.04	2.97	3.14	7.88	0.09
5/29/03	**2.54**	**2.48**	**8.00**	**0.03**	**1.93**	**1.43**	**4.00**	**0.05**
6/09/03	1.94	2.23	5.62	0.03	1.99	1.98	5.40	0.03
6/19/03	0.80	1.05	2.80	0.03	1.65	2.86	10.00	0.03
6/25/04	1.27	1.93	5.89	0.02	2.66	4.15	11.90	0.03
7/02/03	**2.82**	**3.25**	**10.18**	**0.04**	**3.45**	**4.40**	**13.00**	**0.03**
8/13/03	1.79	1.91	5.22	0.08	3.67	3.79	11.19	0.35
10/2/03	1.36	0.80	2.50	0.17	1.42	2.07	7.30	0.10

Table 4-5. Average (AV) vertical saturated hydraulic conductivity on and between strips for the deep chiseled plot (AV = Average, Std = Standard deviation, Max = Maximum, Min = Minimum measured values).

Date	K ($cmhr^{-1}$) – On the strips				K ($cmhr^{-1}$) Between the strips			
	AV	Std	Max	Min	AV	Std	Max	Min
4/02/03	**2.43**	**2.28**	**6.80**	**0.17**	**3.24**	**3.45**	**7.00**	**0.22**
4/10/03	2.81	3.30	7.88	0.09	3.45	3.17	6.49	0.17
5/29/03	**2.05**	**1.37**	**4.00**	**0.05**	**1.57**	**1.85**	**3.70**	**0.40**
6/09/03	2.10	2.19	5.40	0.03	1.64	1.46	2.89	0.04
6/19/03	2.00	3.23	10.00	0.03	0.60	0.99	1.75	0.03
6/25/04	3.07	4.63	11.90	0.03	1.43	2.39	4.19	0.03
7/02/03	**3.98**	**4.96**	**13.00**	**0.03**	**1.84**	**1.65**	**3.31**	**0.05**
8/13/03	3.94	3.99	11.19	0.35	2.86	3.76	7.20	0.57
10/2/03	1.58	2.30	7.30	0.19	0.94	1.35	2.50	0.10

[γ] Bold data shows K readings right after installation of infiltrometers. Other readings were taken after each significant rainfall event but without removing the infiltrometers from their previous installation locations.

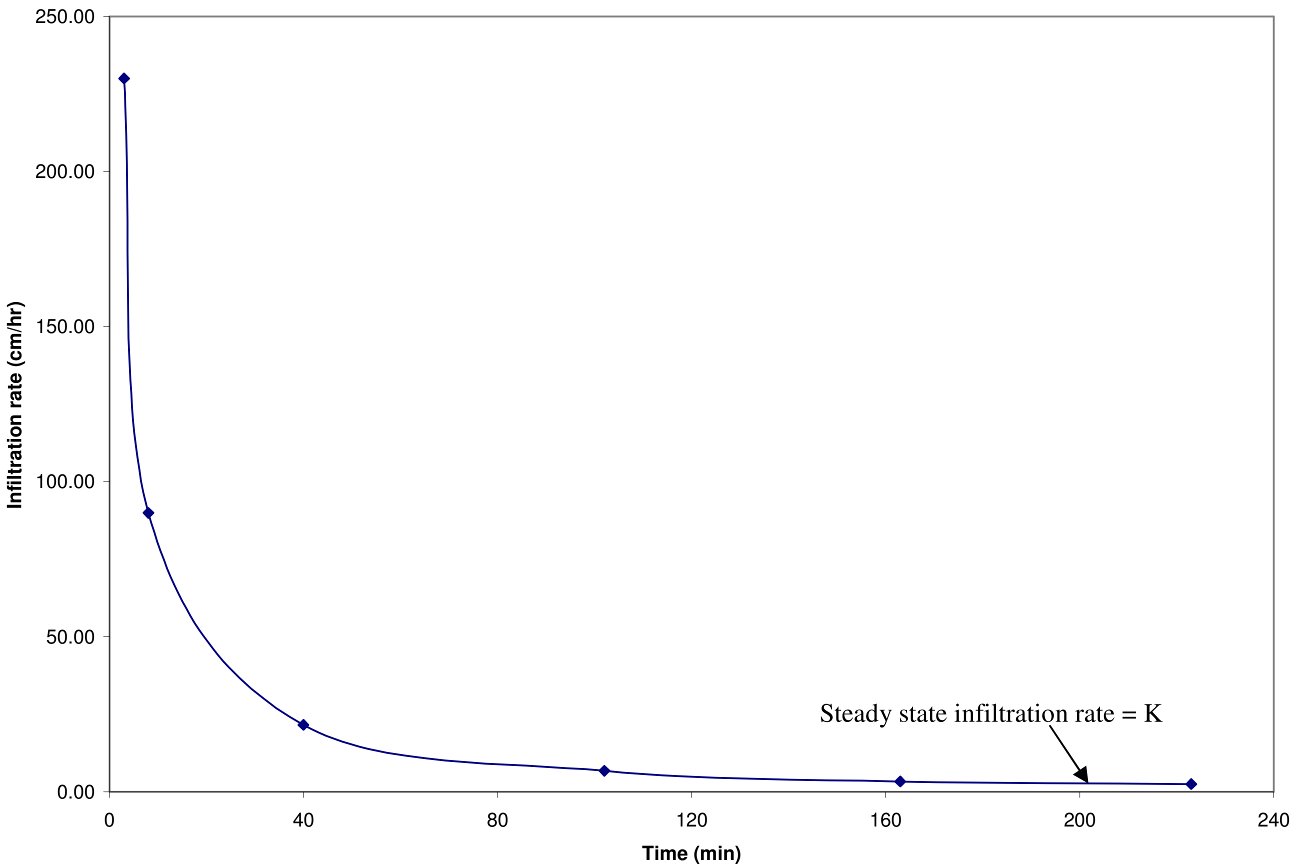


Figure 4-6. Actual infiltration rate versus time graph to show a steady state value used for vertical saturated hydraulic conductivity

4.2.5 Statistical Analysis

A randomized complete block design (RCBD – blocking on date) was used to detect differences between rain gauges, between manual and electronic rain gauges and to determine whether or not the measured data was the same as online data at 5% significance level. The type of RCBD used in this case was the generalized randomized block design (GRBD). A GRBD is a randomized complete block design in which there are b blocks (date) each containing s = rt experimental units, such that each of the t treatments is applied to r (replications per treatment) experimental units (Hinkelmann and Kempthorne, 1994). Blocking reduces and controls experimental error variance to achieve more precision of results. Simple linear regression analysis used to test the effect of water table depth (WTD) on volumetric moisture content (VMC) 10 cm below the ground surface. Finally, nonlinear regression was used to determine whether K varied exponentially with cumulative rainfall since deep chiseling and if not, to determine the trends of the variation of K with cumulative rainfall (R_c) since chiseling. All these analyses were done using SAS (SAS Institute Inc., 1999).

4.3 Results and Discussion

4.3.1 Rainfall Data Analysis

Good and reliable rainfall data was needed to determine how it affected vertical saturated hydraulic conductivity after deep chiseling a Commerce silt loam. Therefore, six manual (Figure 4-4) and two electronic rain gauges located in different places within measurement plots to ensure that rainfall data used was representative. As a final check, rainfall data from a nearby weather station in the same location was downloaded from Louisiana Agriclimatic Information web site (W) (LSU AgCenter Climate, 2004).

Several hypotheses were tested to determine the credibility of the rainfall data and they included:

1. Rainfall amounts, measured by six manual rain gauges randomly placed at different locations had no variability.
2. Rainfall amounts, measured by two electronic rain gauges randomly placed at different locations had no variability.
3. Mean rainfall amount measured by a manual rain gauge (M) was equal to the mean rainfall measured by an electronic rain gauge (E).

4. Mean rainfall amount, for a weather station near the Ben Hur Research site, downloaded from Louisiana Agriclimatic Information web site (W) was equal to the mean rainfall amount measured by the manual and electronic rain gauges (M and E).

Controlling for date, the results from these tests (Table 4-6) showed that there was no significant variability in the amount of rainfall measured by the manual rain gauges (p-value=0.1064) and electronic rain gauges (p-value=0.2475) placed randomly at different locations within the experimental fields. There was a significant difference between the mean rainfall amount measured by the manual and the electronic rain gauges (p-value = 0.0004) and between the mean rainfall amount measured at the nearby weather station (W) and the average of the mean rainfall measured by the manual and electronic rain gauges (E+M) (p-value < 0.0001). The amount of rainfall amounts measured by the three methods are 29 mm, 27 mm and 25 mm for the electronic, manual and website rain gauges respectively. Therefore, care needs to be taken when interpreting the statistical significance in practical terms because these differences are small taking into account that these rainfall amounts were measured in mm.

Table 4-6. Hypothesis testing for rainfall data for Ben Hur Research site blocking on date

Hypothesis	P-value
$\sigma_m^2 = 0$	0.1064
$\sigma_e^2 = 0$	0.2475
$\mu_m = \mu_e$	0.0004
$\mu_w = \mu_{(e+m)/2}$	<0.0001

It is important to point out that although there was no significant difference in the amount of rainfall for at different locations, this is not always the case because amount of rainfall measured varies depending on the size, direction and speed (intensity) of the rain event. However, in cases where rainfall data for a particular research field is not available, one can download rainfall data for a weather station closest to the field from the web site, which could be a reasonable approximation. Finally, although there were statistical differences in the amount measured using electronic, manual and website rain gauges, practical significance may be different from statistical significance.

4.3.2 Relationship between Water Table Depth and Volumetric Moisture Content

There was a significant linear relationship between volumetric moisture content (VMC) between 5 cm and 10 cm below the ground surface and water table depth (WTD) for both the deep chiseled plot (p-value =0.0036) and non deep chiseled plot (p-value = 0.0002). Despite these significant slopes, the percentage of explained variation in WTD caused by VMC is very modest at $R^2 = 0.08$ for the deep chiseled plot and $R^2 = 0.16$ for the non-deep chiseled plot. In other words there is a large variance around the regression line as shown in Figure 4-7 and Figure 4-8.

The following are possible reasons for the large variance around the regression line. Generally, in any given plot, the soil properties are heterogeneous and since the volumetric moisture content measurements were taken at different locations within a given plot, there may have been a likelihood that the measured VMC values varied from location to location. Another possible reason is that VMC on the soil top layer could be affected by other variables for instance compaction from machine traffic. Other potential reasons include plant withdrawal, evaporation demand and recent rainfall.

It is therefore, recommended that volumetric moisture content be measured at different deeper depths within the soil profile to determine an optimum depth at which the correlation between WTD and VMC is good. This information could be used to predict the soil moisture content, at a given soil profile depth, using the easier-to-measure water table depth under stable conditions.

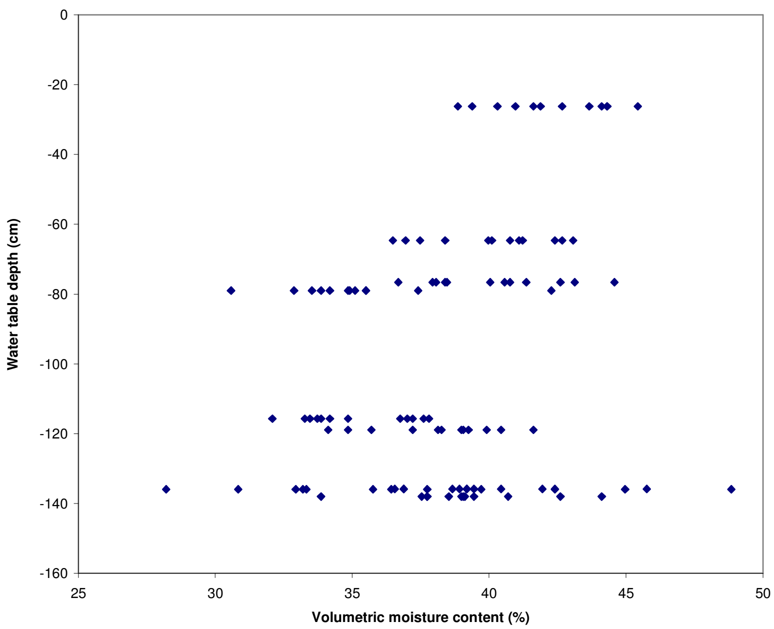


Figure 4-7. Correlation between water table depth and volumetric moisture content for the deep chiseled plot

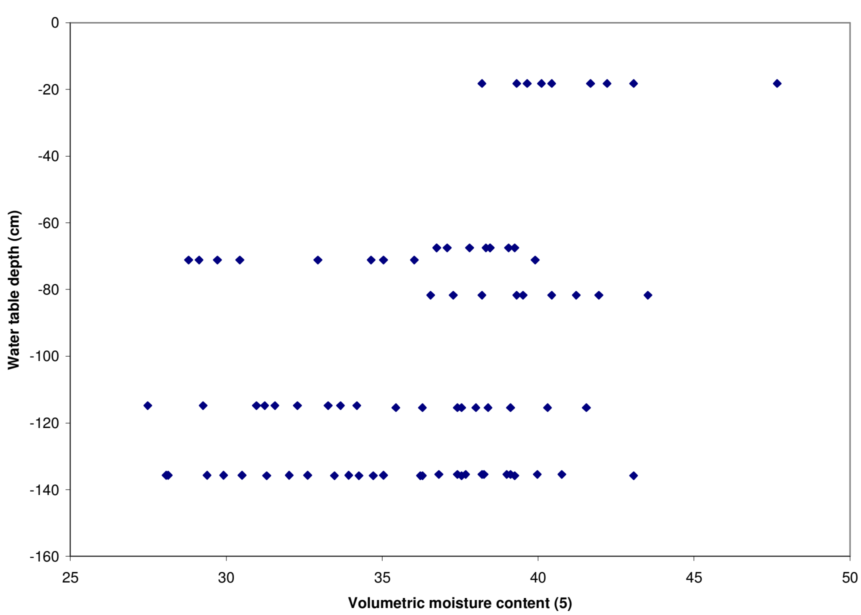


Figure 4-8. Correlation between water table depth and volumetric moisture content for the non-deep chiseled plot

4.3.3 Comparison of Volumetric Moisture Content between the Deep Chiseled and Non-deep Chiseled Plot

Because one plot was deep chiseled (treatment) to break the soil surface seal while the other was not deep chiseled, the null hypothesis was that the deep chiseled plot had higher volumetric moisture content than the plot the non-deep chiseled plot because of potential increase in the infiltration rates caused by deep chiseling. A randomized complete block design (RCBD) was used to determine how significant the treatment of interest, deep chiseling, was. Blocking on date was done to remove variability from date to date to gain more precision for the treatment effect. Since there was replication within each date/treatment combination, test for significant date/treatment interaction was tested. There was a significant overall main effect that the volumetric moisture content on the deep chiseled plot was significantly higher than on the non-deep chiseled plot (p-value = 0.0001). However, a significant interaction between date and the deep chiseling operation was found (p-value = 0.0287) suggesting that the strength of deep chiseling effect on volumetric moisture content varies from date to date as shown in Figure 4-9.

Least significant difference (LSD) post hoc comparison (Table 4-7) showed that only during 3 (mainly initially) out of 9 dates was the VMC for the deep chiseled plots significantly higher than that for non-deep chiseled plot. Therefore, the date the measurements were taken had a significant effect on the volumetric moisture content. A possible reason is given by Figure 4-9 which shows that about 4 months (and 48 cm of cumulative rainfall) after deep chiseling the plots, volumetric moisture content measurements for both plots were not significantly different, which may imply that the soil surface had sealed for the deep chiseled plot. Another possible reason is that machine traffic on the deep chiseled plot, in addition to further high-energy raindrops, may have increased soil compaction to the value just before deep chiseling.

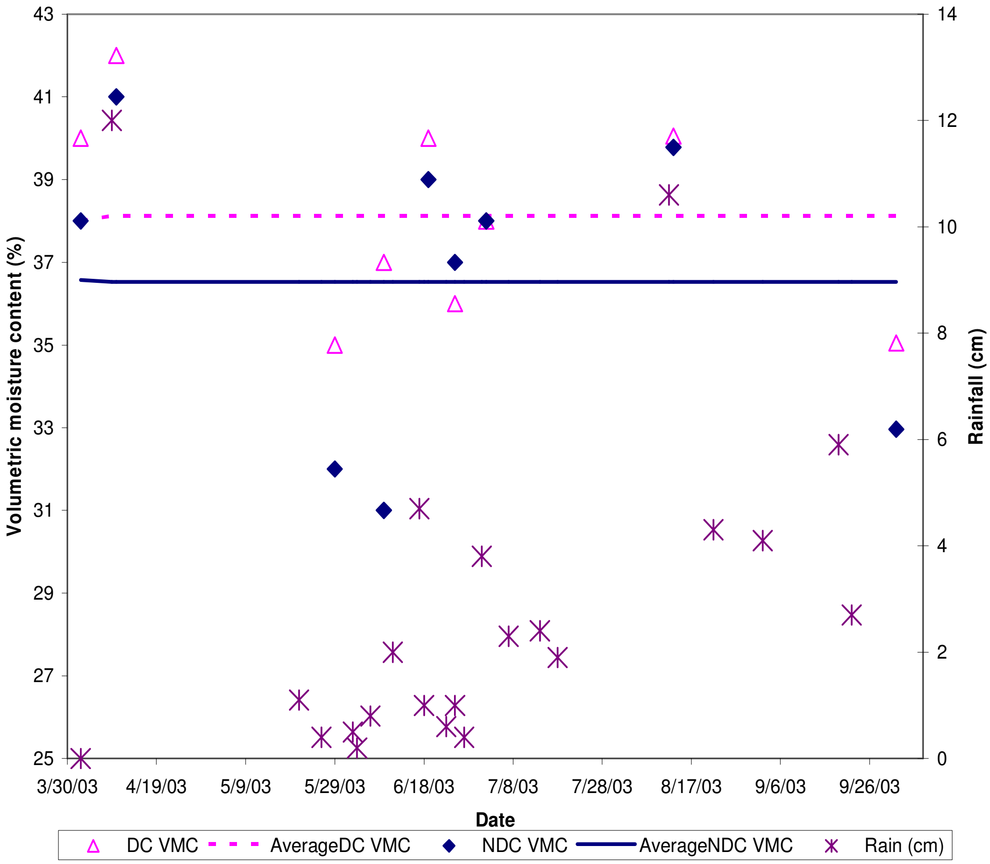


Figure 4-9. Volumetric moisture content for the deep chiseled (DC VMC) and for the non-deep chiseled plot (NDC VMC) – between 4/02/03 and 10/02/03

Table 4-7. LSD post hoc comparison between volumetric moisture content (VMC) for the deep chiseled (DC) plot and the non-deep chiseled NDC) plot

Date	Treatment		P-value
	Mean DC VMC (%)	Mean NDC VMC (%)	
04/02/2003	40	38	0.0641
04/10/2003	42	41	0.4704
05/29/2003	35	31	0.0038
06/09/2003	37	31	0.0001
06/19/2003	40	39	0.3818
06/25/2003	39	36	0.0238
07/02/2003	38	38	0.9825
08/13/2003	40	40	0.9128
10/02/2003	35	33	0.0891

4.3.4 Comparison of Soil Bulk Density between the Deep Chiseled and Non-deep Chiseled Plot

To determine the effect of compaction of vertical saturated hydraulic conductivity, data from the deep chiseled and control plot were analyzed using randomized complete block design, blocking on the date. The null hypothesis was that the mean bulk density for the deep chiseled plot was less than that for non-deep chiseled plot. There was a significant overall deep chiseling effect on soil bulk density, with soil bulk density for the deep chiseled plot being higher than that for the non-deep chiseled plot (p-value = 0.0059). The date/deep chiseling interaction was significant (p-value = 0.0046) as shown by Figure 4-10, which suggests that strength of deep chiseling on the soil bulk density varies from date to date and because the date might be a proxy to weather. An LSD post hoc comparison (Table 4-8) showed that only during 3 out of 9 dates was the soil bulk density for the deep chiseled plots significantly different from those for non-deep chiseled plot, which supports the significant date/deep chiseling interaction. A possible explanation was that the soil layer for two plots might have been compacted during seedbed preparation, planting and nitrogen and pesticide application operations.

Table 4-8. Post hoc comparison between soil bulk density (BD) for the deep chiseled (DC) plot and the non-deep chiseled NDC) plot

Date	Treatment		P-value
	Mean DC BD (g/cm^3)	Mean NDC BD (g/cm^3)	
04/02/2003	1.61	1.61	0.8440
04/10/2003	1.55	1.62	0.0380
05/29/2003	1.76	1.78	0.4939
06/09/2003	1.80	1.72	0.0080
06/19/2003	1.63	1.75	0.0003
06/25/2003	1.65	1.66	0.6626
07/02/2003	1.62	1.67	0.1227
08/13/2003	1.64	1.68	0.2855
10/02/2003	1.71	1.75	0.1775

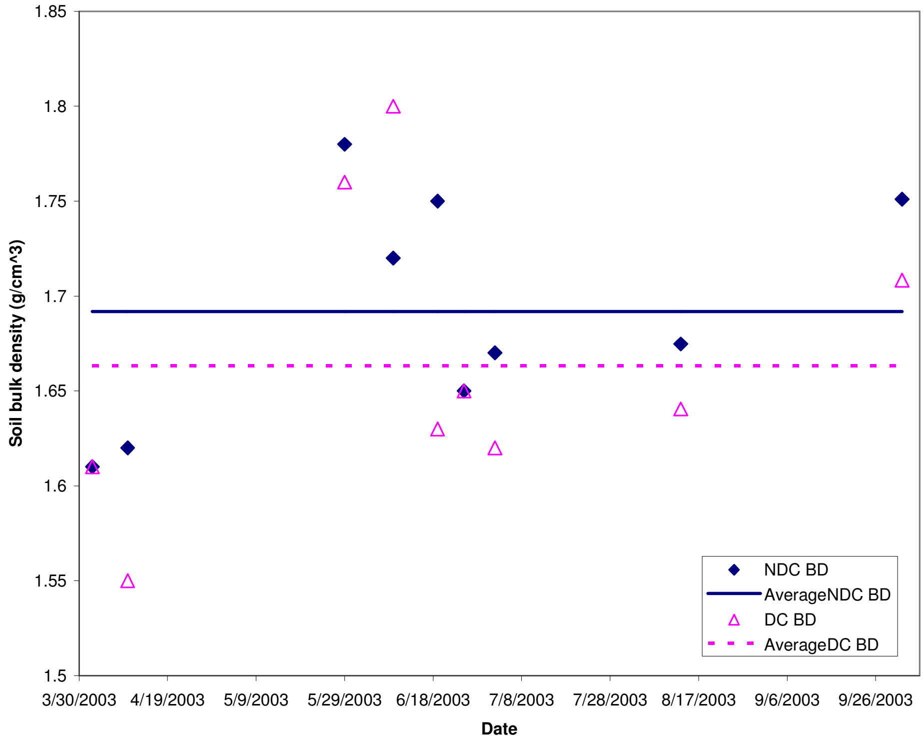


Figure 4-10. Soil bulk density for the deep chiseled plot (DC BD) and the non-deep chiseled plot (NDC BD) – between 4/02/03 and 10/02/03

4.3.5 Comparison of Water Table Depths between the Deep Chiseled and Non-deep Chiseled Plot

To determine the effect of deep chiseling on the water table depth, it was hypothesized that the deep chiseled plot would have shallower water tables than the plot that was not deep chiseled. The idea behind this hypothesis was that since the pore space for the deep chiseled plot is higher than the non deep chiseled plot, more water will infiltrate into the subsurface layers of soil for the deep chiseled plot and therefore increase (closer to ground surface) the water table depth. Therefore, if this hypothesis was true, it would mean that there was more water infiltration and hence less surface runoff. Using RCBD to test the effect of deep chiseling on water table depth (WTD) showed that there was no significant overall main deep chiseling effect on water table depth, which means that the water table depths within the deep chiseled plot and the non-deep chiseled plot were not significantly different (p-value = 0.9521) as illustrated by Figure 4-11. However, because there were no replications, date/deep chiseling interaction was not tested.

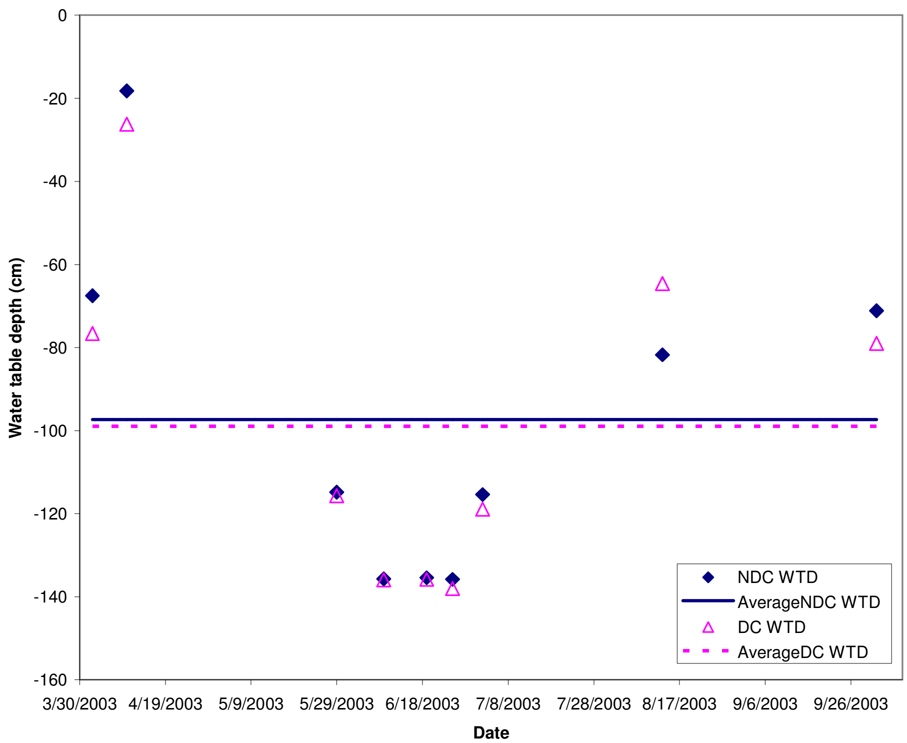


Figure 4-11. Comparison of water table depth between the deep chiseled plot (DC WTD) and the non-chiseled plot (NDC WTD)

With an exception of one day (August 12, 2003) when the amount of rainfall was 10.6 cm, there was no significant difference in the WTD on the deep chiseled plot and the non-deep chiseled plot. On August 12, 2003, the water depth was significantly shallower on the deep chiseling plot than on the non-deep chiseled plot implying that deep chiseling improves infiltration. Possible explanations for the insignificant difference between the WTD on the deep chiseled plot and the non-deep chiseled plot include the following. Crop roots penetration deeper on a deep chiseled plot thus removing water from the deep chiseled plot hence would lead to a deeper water table depth, which may be close the

WTD for the non-deep chiseled plot, which has less vertical saturated hydraulic conductivity. The soil surface would have sealed significantly because of the 25 cm of rainfall before measurements were taken and soil top-layer machine compaction during seedbed preparation, planting and nutrient application operations. Also water table depth depends on the amount of rainfall in a given time, which means that if there is an insufficient amount of rainfall, although the upper soil layers might be wetter, the water table depths would not be significantly different between the deep chiseled plot and the non deep chiseled plot.

4.3.6 The Effect of Water Table Depth and/or Volumetric Moisture Content on the Measured Vertical Saturated Hydraulic Conductivity

There was no significant linear relationship between water table depth (WTD) and vertical saturated hydraulic conductivity (K) (p-value = 0.3577). However, there was a significant linear relationship between volumetric moisture content (VMC) and K (p-value = 0.0033). Despite these significant slopes, the percentage of explained variation in K caused by WTD is very modest at $R^2 = 0.01$ for the deep chiseled plot and in K caused by VMC at $R^2 = 0.08$ for the same deep chiseled plot. In other words, there is a large variance around the regression line as shown in Figure 4-12. This information could help explain the trends in vertical saturated hydraulic conductivity depending on the on the amount of rainfall over time (cumulative rainfall) since deep chiseling a plot.

4.3.7 Vertical Saturated Hydraulic Conductivity Data Analysis

The goal of this research was to determine the variation in vertical saturated hydraulic conductivity (K) with cumulative rainfall after deep chiseling a Commerce silt loam soil. The analyses of other data gathered as presented and discussed in sections

4.3.1 through 4.3.6 was intended to help understand the prevailing conditions at the time of K measurements. This information could help explain some of the trends noted.

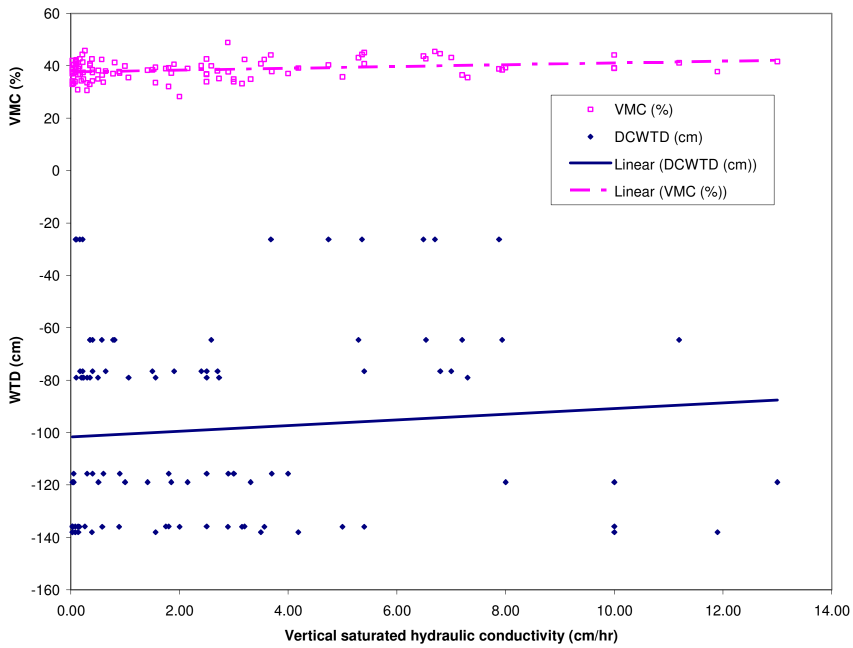


Figure 4-12. Relationship between water table depth (WTD) and the volumetric moisture content (VMC) and the vertical saturated hydraulic conductivity, K

4.3.7.1 Comparison between Vertical Saturated Hydraulic Conductivity Measurements for the Deep Chiseled and Non-deep Chiseled Plots

To determine whether deep chiseling (treatment) a plot does increase vertical saturated hydraulic conductivity (K), a randomized complete block design (blocking on date) was applied on measurements from the deep chiseled plot and the plot that was not deep chiseled (control). It was hypothesized that K for the deep chiseled plot was greater than K for the plot that was not deep chiseled. Controlling on date the results revealed that there was a significant overall deep chiseling effect on K, which means that the mean K value for the deep chiseled plot was significantly different (higher) from the mean K value for the non-deep chiseled plot (p-value = 0.0320). However, there was no date/deep chiseling interaction (p-value = 0.3794) as shown in Figure 4-13.

An LSD post hoc comparison (Table 4-9) showed that only during 1 out of 9 dates was the vertical saturated hydraulic conductivity for the deep chiseled plots significantly higher than that for non-deep chiseled plot. However, in most cases the K values for the deep chiseled plot were higher compared with those on non-deep chiseled plot, which supports the significant overall main effect. This showed that deep chiseling treatment increased K.

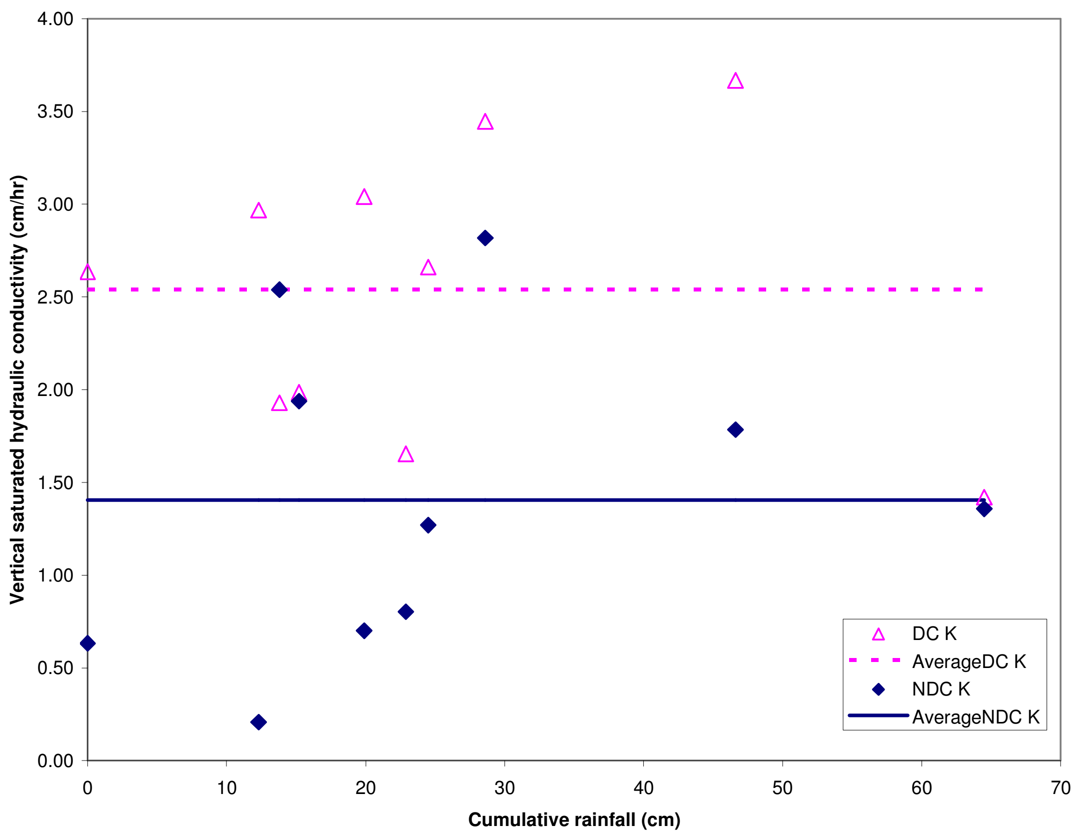


Figure 4-13. Comparison of vertical saturated hydraulic conductivity measurements on a deep chiseled plot (DC K) and the non-deep chiseled plot (NDC K)

Table 4-9. Post hoc comparison between K measurements for the deep chiseled (DC) plot and the non-deep chiseled NDC) plot

Date	Treatment		P-value
	Mean DC K (cm/hr)	Mean NDC K (cm/hr)	
04/02/2003	2.64	0.63	0.1016
04/10/2003	2.97	0.21	0.0246
05/29/2003	1.93	2.54	0.6171
06/09/2003	1.99	1.94	0.9693
06/19/2003	1.65	0.80	0.4856
06/25/2003	2.66	1.27	0.2548
07/02/2003	3.45	2.82	0.6061
08/13/2003	3.67	1.78	0.1238
10/02/2003	1.42	2.48	0.3859

The next question to investigate was whether there was a difference in the measured vertical saturated hydraulic conductivity values on the strip and between the strips (Figure 4-4) in order to determine representative K values to be used in the final analysis.

4.3.7.2 Comparison between Vertical Saturated Hydraulic Conductivity Measurements on the Strip and between the strips for the Deep Chiseled Plot

It was hypothesized that vertical saturated hydraulic conductivity (K) measurements on the strip would be higher than the measurements between strips. As in the previous sections, a randomized complete block design (blocking on date) was used to analyze the effect deep chiseling strip on K. Results shown in Figure 4-14 revealed that there was no significant difference between K measurements on the strips and those between the strips (p-value = 0.3174). There was no interaction between the location of measurement and the date (p-value = 0.9873).

A possible reason for the contrary result would be that some of the infiltrometers, which were to be installed between the deep chiseled strips, might have been installed on the strips the first time. This could have been caused by erroneous distances of the infiltrometer location from the reference point as described in section 4.2.2 because these distances were measured once widthwise and assumed to remain perpendicular from one end of the plot to the other. However, when these infiltrometers were reinstalled after nitrogen application (5/29/03), K measurements on the strips remained higher until the completion of the experiment. If the first two data points are taken as potential outliers, RCBD analysis on the remaining data showed that the K measurements on the strips were significantly higher than K measurements between the strips (p-value = 0.03).

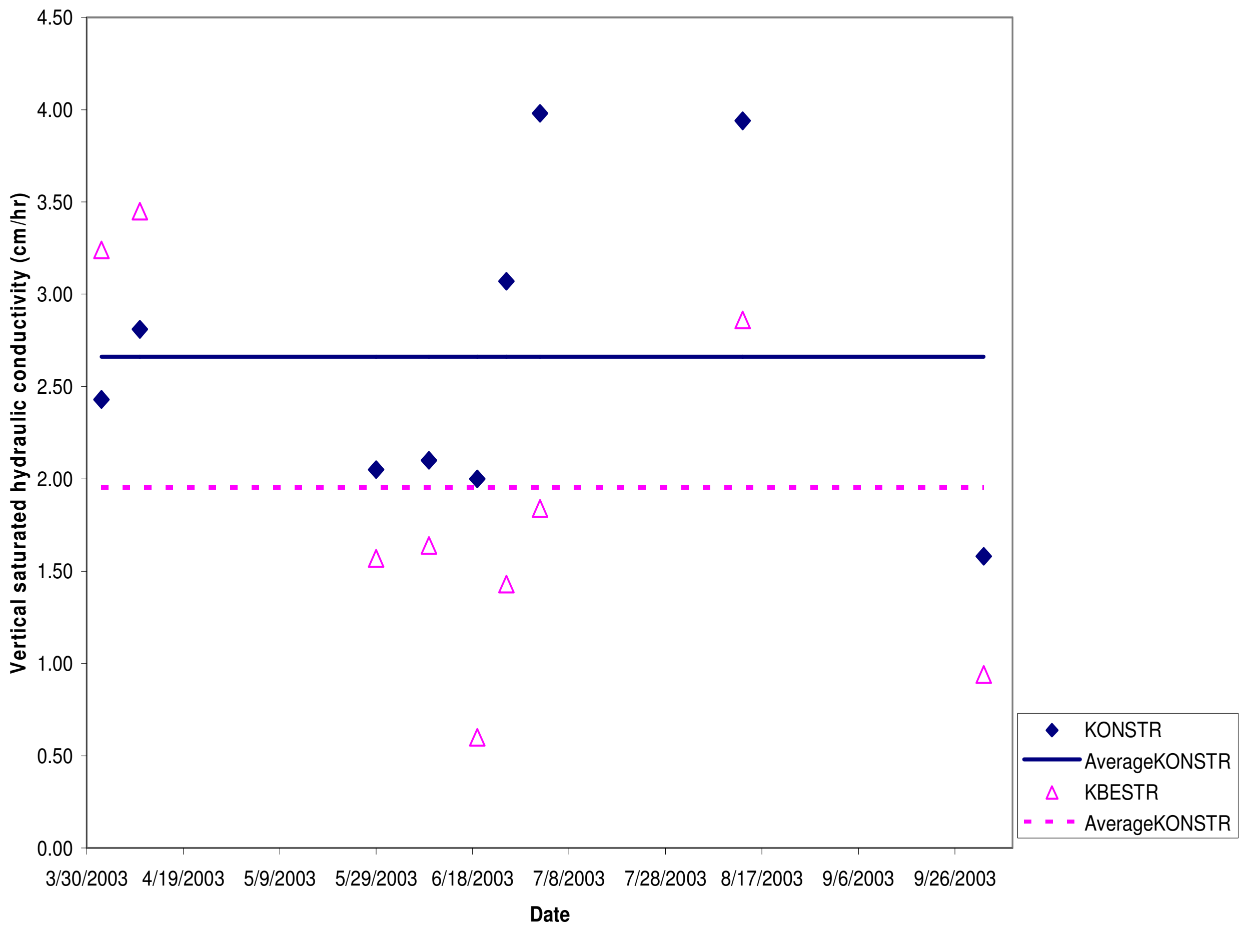


Figure 4-14. Comparison of vertical saturated hydraulic conductivity measurements on the strip (KONSTR) and between the strips (KBESTR) for the deep chiseled plot - from 4/02/03 to 10/02/03

Therefore, average values of K measurements both on the strip and between the strips were used as representative values to determine how K varied with cumulative rainfall after deep chiseling a Commerce silt loam soil.

4.3.7.3 Variation of Vertical Saturated Hydraulic Conductivity Measurements Depending on Cumulative Rainfall after Deep Chiseling a Commerce Silt Loam Soil

Kim and Chung (1994) found that average saturated hydraulic conductivity on a tilled sandy loam soil layer gradually decreased exponentially as a function of cumulative rainfall energy after tillage. Average saturated hydraulic conductivity right after tillage was about 45.42 cm/hr; about four times the average saturated hydraulic conductivity before tillage and stabilized at a value of 8.64 cm/hr. According to Rao et al. (1998b), the decline in infiltration rate since tillage was found to have an exponential relationship with cumulative rainfall since tillage, decreasing from a maximum rate of 610 mm/hr to a relatively steady rate of 9.6 mm/hr.

However, statistical analysis using data collected from the Commerce silt loam soil showed that there was no exponential relationship (Figure 4-15) between vertical saturated hydraulic conductivity and cumulative rainfall (R_c) after deep chiseling ($R^2 = 0.05$). Possible reasons for the poor exponential relationship include the fact that by the time vertical saturated hydraulic conductivity measurements were made, there had been a cumulative rainfall of 24.7 cm since deep chiseling. Prior work on an Alfisol (clayey skeletal, mixed, isohyperthermic, udic rhodustalfs) (Rao et al., 1998b), showed that tillage benefits of increased infiltration were lost after a single storm of 11.5 cm in 1989 and after a cumulative rainfall of 15.0 cm from small (2.0 cm) rain events. Another possible reason could be due to entrapped air (Rao et al., 1998a; Reynolds and Elrick, 1989; Bouwer, 1966) as explained by Figures 4-16, 4-17 and 4-18.

Although there was no exponential relationship as expected based on the previous work (Allen and Musick, 2001; Rao et al, 1998b; Kim and Chung, 1994), a second order polynomial regression line fitted the collected data relatively well ($R^2 = 0.76$) (Figure 4-16). The polynomial relationship exhibited by Figure 4-16 was an effort to determine possible explanation why there was no exponential relationship as expected (Allen and Musick, 2001; Rao et al, 1998b; Kim and Chung, 1994) and is therefore not necessarily a true relationship.

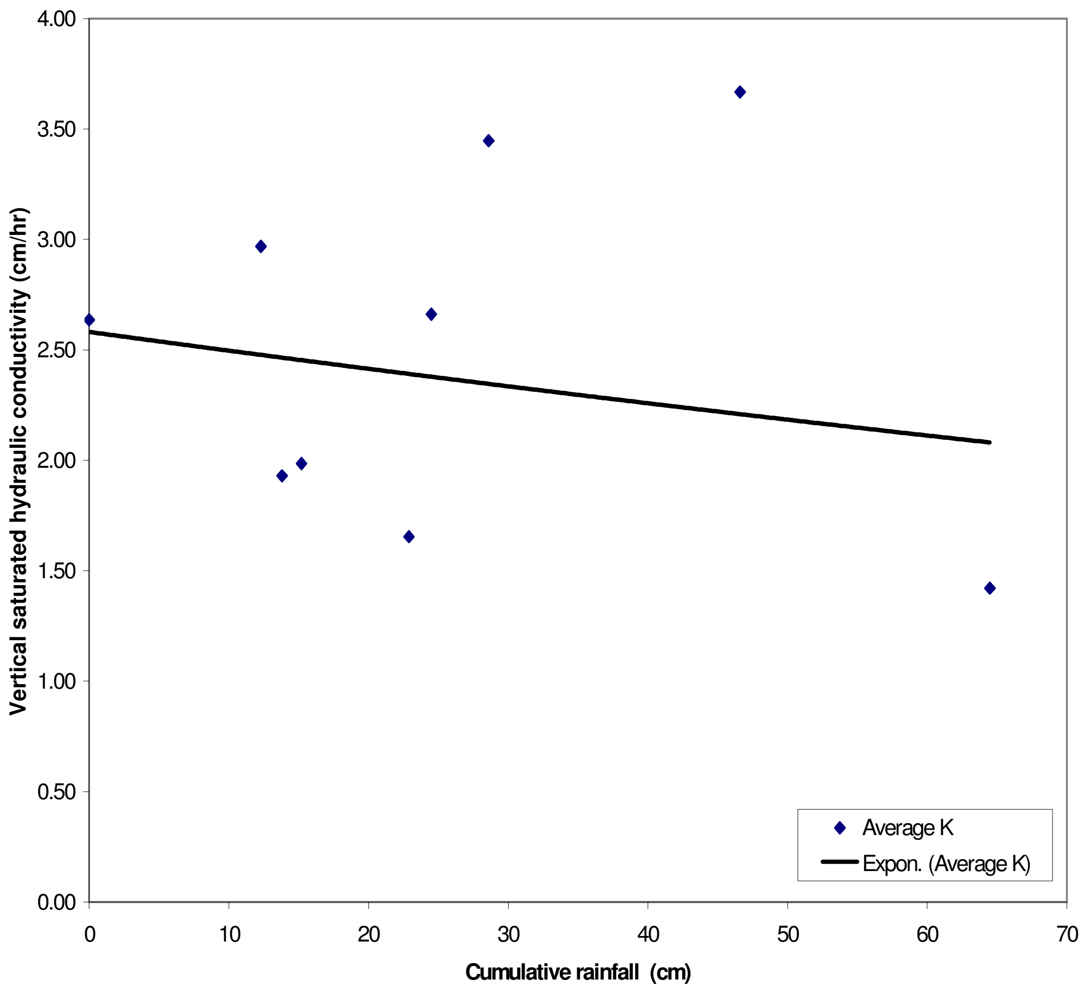


Figure 4-15. Poor exponential relationship between cumulative rainfall and vertical saturated hydraulic conductivity

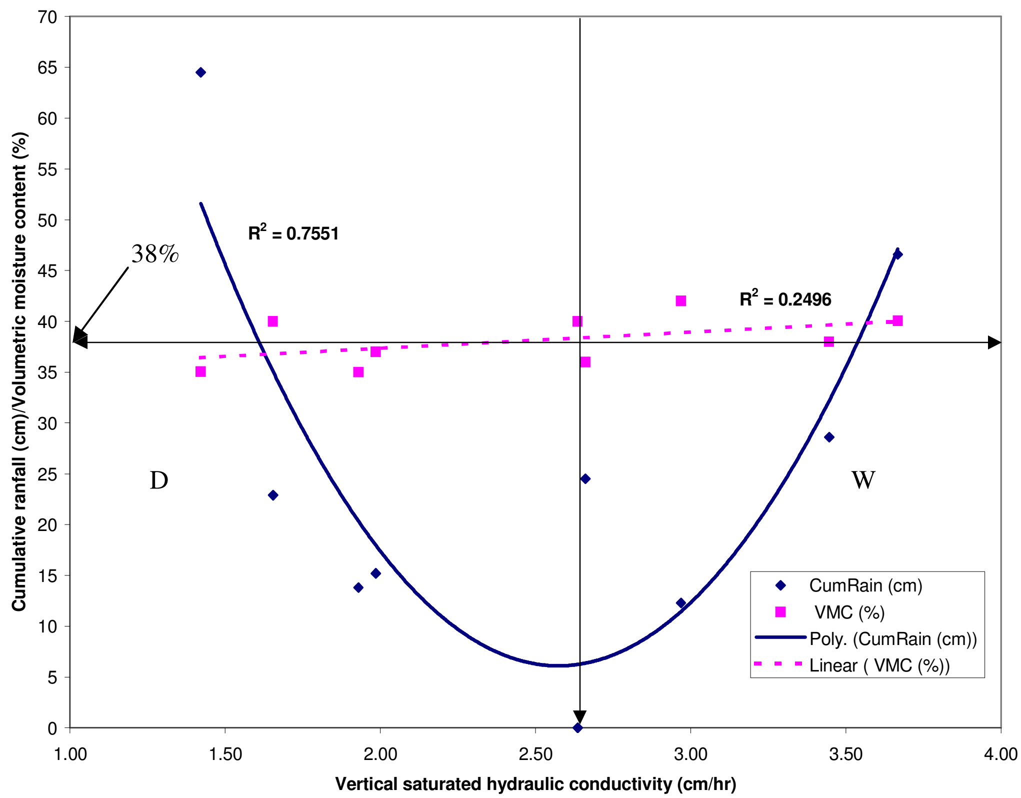


Figure 4-16. Variation of vertical saturated hydraulic conductivity depending on cumulative rainfall since deep chiseling Commerce silt loam soil, with additional effect of soil moisture content.

Figure 4-16 shows the relationship between both cumulative rainfall and volumetric moisture content, and vertical saturated hydraulic conductivity. The relationship between volumetric moisture content and vertical saturated hydraulic conductivity is a weak linear one ($R^2 = 0.25$). Combining this weak linear relationship with that of a second order polynomial relationship fitted between cumulative rainfall since deep chiseling and vertical saturated hydraulic conductivity, resulted in dividing the collected data into the dry (D) and wet (W) regions using 38% volumetric moisture content (VMC) as the borderline (that is a VMC of less than 38% considered dry). Two sets of data points were generated and analyzed (Figure 4-17 and Figure 4-18).

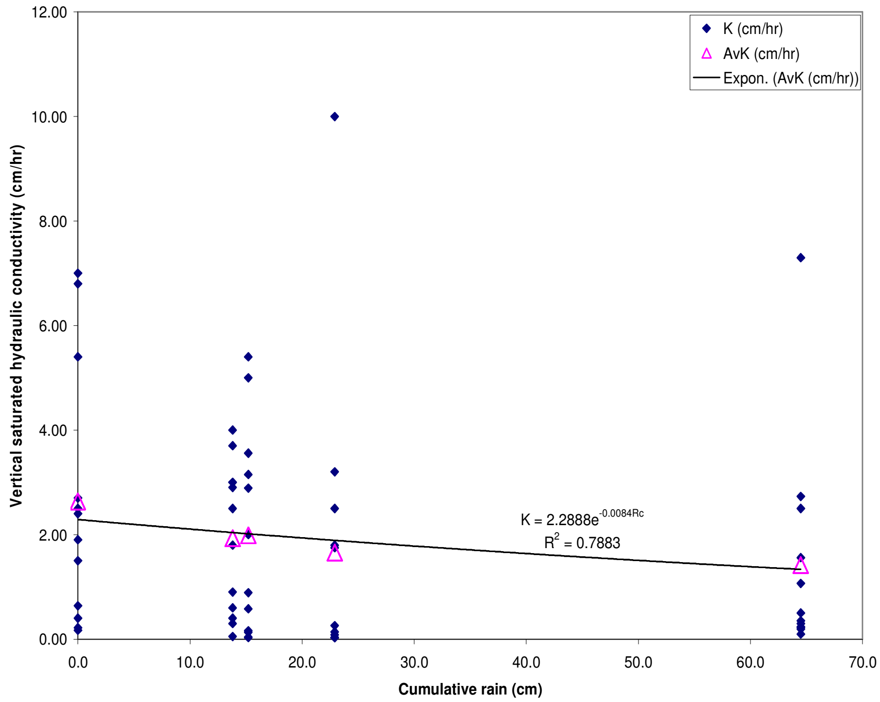


Figure 4-17. Exponential decrease in vertical saturated hydraulic conductivity after deep chiseling as cumulative rainfall increases when soil volumetric moisture content is <38%.

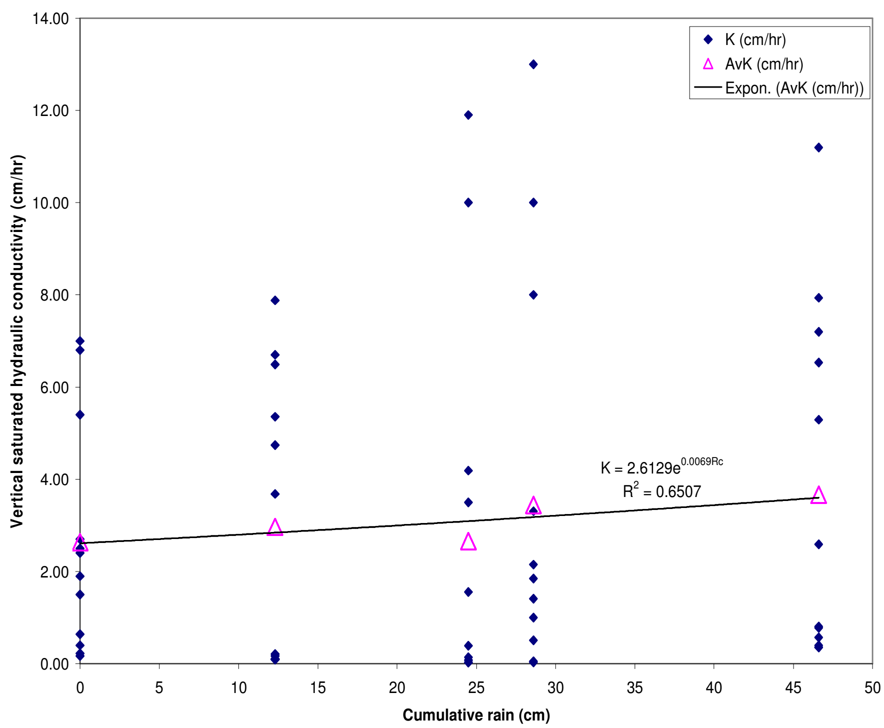


Figure 4-18. Exponential increase in vertical saturated hydraulic conductivity after deep chiseling as cumulative rainfall increases when soil volumetric moisture content is >38%.

Using nonlinear regression, an exponential relationship (model) between the average K and R_c using dry (Figure 4-17) and wet (Figure 4-18) data yielded relatively good results with dry (R^2 = 0.79) data giving a better regression than wet (R^2 =0.65). It is important to note the large variability in the K measured at different locations of the field. Based on the a "critical" volumetric moisture content specific for the data collected (38%), the K measurements taken on days when volumetric moisture content was less than 38% showed that vertical saturated hydraulic conductivity decreased exponentially with increasing cumulative rainfall after deep chiseling a Commerce silt loam, a southern alluvial soil. On the other hand K measurements taken when the volumetric moisture content was greater than 38% ("wet") resulted in a nonlinear relationship in which vertical saturated hydraulic conductivity increased exponentially with increasing cumulative rainfall after deep chiseling (Figure 4-18).

The explanation for an exponential increase in vertical saturated hydraulic conductivity (K) with increase in cumulative rainfall after deep chiseling is not known. However, it was observed that K measurements under dry conditions were significantly lower than under wet conditions (p-value=0.002). This result supports work by Rao et al. (1998a) who found that for events with more than 15 mm of rain during the previous two days, infiltration rates were generally higher than for dry soil. This may be due to entrapped air within the pore spaces in dry soils.

According to Bouwer (1966), true saturated conditions rarely occur in the vadose zone except where restrictive layers result in perched water tables because of the entrapped air. The entrapped air prevents water movement in air-filled pores, which consequently, may reduce the hydraulic conductivity measured in the field by as much as

50 percent compared to conditions when trapped air is not present (Reynolds and Elrick, 1986).

4.4 Conclusions

Controlling for date (randomized complete block design) , the rainfall data analysis results showed that there was no significant variability in the amount of rainfall measured by the manual rain gauges (p-value=0.1064) and electronic rain gauges (p-value=0.2475) placed randomly at different locations within the experimental fields. There was a significant difference between the mean rainfall amount measured by the manual and the electronic rain gauges (p-value = 0.0004) and between the mean rainfall amount measured at the nearby weather station (W) and the average of the mean rainfall measured by the manual and electronic rain gauges (E+M) (p-value < 0.0001). However, care needs to be taken when interpreting the statistical significance in practical terms because these differences are small taking into account that these rainfall amounts were measured in mm.

There was a significant linear relationship between volumetric moisture content (VMC) between 5 cm and 10 cm below the ground surface and water table depth (WTD) for both the deep chiseled plot (p-value =0.0036) and non deep chiseled plot (p-value = 0.0002). Despite these significant slopes, the percentage of explained variation in WTD caused by VMC is very modest at $R^2 = 0.08$ for the deep chiseled plot and $R^2 = 0.16$ for the non-deep chiseled plot. In other words, there is a large variance around the regression line. Possible reasons for the large variance around the regression line include the heterogeneous nature of soil properties from location to location. Another possible reason is that VMC on the soil top layer could be affected by other variables for instance compaction from machine traffic. Other potential reasons include plant withdrawal, evaporation demand and recent rainfall. It is therefore, recommended that volumetric moisture content be measured at different deeper depths within the soil profile to determine an optimum depth at which the correlation between WTD and VMC is good. This information could be used to predict the soil moisture content, at a given soil profile depth, using the easier-to-measure water table depth under stable conditions.

Randomized complete block design tests on the effect of deep chiseling on volumetric moisture content showed that volumetric moisture content on the deep chiseled plot was significantly higher than on the non-deep chiseled plot (p-value = 0.0001). However, a significant interaction between date and the deep chiseling operation was found (p-value = 0.0287) suggesting that the strength of deep chiseling effect on volumetric moisture content varies from date to date. Possible reasons for this significant interaction a potential soil seal formation approximately 4 months due to a cumulative rainfall of 48 cm after deep chiseling the plot coupled with normal machine traffic, which could have caused further soil compaction.

Regarding the soil bulk density, there was a significant overall deep chiseling effect on soil bulk density, with soil bulk density for the deep chiseled plot being higher than that for the non-deep chiseled plot (p-value = 0.0059). The date/deep chiseling interaction was significant (p-value = 0.0046), which suggests that strength of deep chiseling on the soil bulk density varies from date to date and because the date might be a proxy to weather. A possible explanation was that the soil layer for two plots might have been compacted during seedbed preparation, planting and nitrogen and pesticide application operations. Further use of RCBD to test the effect of deep chiseling on water table depth (WTD) showed that there was no significant overall main deep chiseling effect on water table depth, which means that the water table depths within the deep chiseled plot and the non-deep chiseled plot were not significantly different (p-value = 0.9521). However, because there were no replications, date/deep chiseling interaction was not tested.

Statistical analysis revealed that there was no significant linear relationship between water table depth (WTD) and vertical saturated hydraulic conductivity (K) (p-value = 0.3577). However, there was a significant linear relationship between volumetric moisture content (VMC) and K (p-value = 0.0033). Despite these significant slopes, the percentage of explained variation in K caused by WTD is very modest at R^2 = 0.01 for the deep chiseled plot and in K caused by VMC at R^2 = 0.08 for the same deep chiseled plot. In other words, there is a large variance around the regression line. This information could help explain the trends in vertical saturated hydraulic conductivity depending on the on the amount of rainfall over time (cumulative rainfall) since deep chiseling a plot.

Controlling for date, further results revealed that there was a significant overall deep chiseling effect on K, in which the mean K value for the deep chiseled plot was significantly different (higher) from the mean K value for the non-deep chiseled plot (p-value = 0.0320). However, there was no date/deep chiseling interaction (p-value = 0.3794). This showed that deep chiseling treatment increased K. Further tests on the location effect revealed that there was no significant difference between K measurements on the strips and those between the strips (p-value = 0.3174). There was no interaction between the location of measurement and the date (p-value = 0.9873).

Therefore, the mean values of K measurements both on the strip and between the strips were used as representative values to determine how K varied with cumulative rainfall after deep chiseling a Commerce silt loam soil.

Vertical saturated hydraulic conductivity had mixed variations depending on cumulative rainfall after deep chiseling a Commerce silt loam, a southern alluvial soil. Average vertical saturated hydraulic conductivity decreased exponentially with increasing cumulative rainfall for measurements taken when the soil volumetric moisture content was less than 38% (R^2 = 0.79). On the contrary average vertical saturated hydraulic conductivity increased exponentially with increasing cumulative rainfall for measurements taken when the soil volumetric moisture content was equal or greater than 38% (R^2 = 0.65). This result could not be explained. Vertical saturated hydraulic conductivity (K) measurements taken when the soil volumetric moisture content (VMC) was less than 38% were significantly lower than K measurements taken when VMC was equal or greater than 38% (p-value = 0.002). A possible reason for the lower vertical saturated hydraulic conductivity could be entrapped air (Bouwer, 1966), which prevents water movement in air-filled pores consequently reducing the hydraulic conductivity measured in the field by as much as 50 percent compared to conditions when trapped air is not present (Reynolds and Elrick, 1986).

Further work is needed to determine if the variability of vertical saturated hydraulic conductivity (K) with respect to cumulative rainfall (R_c) after deep chiseling can be replicated. Other possible factors that could affect vertical saturated hydraulic conductivity would need to be investigated to determine why K exponentially increases with increasing R_c. One possible factor for investigation could be to have a model that would correlate entrapped air with soil volumetric moisture content and hence water table depth to determine the current correction factor instead of using an assumed fixed factor (Skaggs, 1980).

Although there was no clear-cut relationship between vertical saturated hydraulic conductivity and cumulative rainfall after deep chiseling, information gained from this research could be used to calibrate a dynamic vertical saturated hydraulic conductivity model. If such a model could be written and incorporated into DRAINMOD, it could lead to improved prediction of soil water infiltration and surface runoff.

CHAPTER FIVE

MODELING THE EFFECTS OF DEEP CHISELING WITHIN DRAINMOD FOR ALLUVIAL SOILS: DEVELOPMENT OF THE DRAINMOD-K_S AND DRAINMOD-STMAX MODELS AND SENSITIVY OF PARAMETERS

5.1 Introduction

Short duration and high intensity rainfall (Bengtson and Carter, 2004; Keim and Faiers, 1996; Fouss et al., 1987) on alluvial soils in the Lower Mississippi River Valley (LMRV) leads to soil surface seal formation (Martinez-Gamino, 1994) especially during seedbed preparation and planting periods when the soil is bare. Machine traffic and compaction tend to accelerate the sealing/crusting problem. A tillage operation that has been used in Louisiana to break the soil surface crust and the hard pan in order to increase infiltration and reduce surface runoff is deep chiseling (Bengtson et al, 1995). Deep chiseling increases infiltration and reduces surface runoff by increasing the vertical component of saturated hydraulic conductivity (K_s) of the top layer of soil and increasing the maximum surface depressional storage (STMAX) (Kincaid, 2002). Unfortunately, the benefits of deep chiseling are only temporary because the soil surface seal reforms and soil compaction increases gradually to the previous condition as the fine particles fill the soil pore spaces and surface depressions are smoothed out after subsequent rainfall events (Freebairn et al., 1991).

A detailed description of how K_s and STMAX are used by DRAINMOD model to compute infiltration, surface runoff and surface storage is given in section 2.7 of chapter two. DRAINMOD is a computer model that was developed at North Carolina State University in the late 1970s (Skaggs, 1978). This model is based on the water balance in the soil profile and uses long-term (20 - 40 years) climatological records to simulate the performance of drainage and water table control systems on a continuous basis.

Although K_s and STMAX decrease gradually depending on total rainfall (Freebairn et al., 1991) over time [cumulative rainfall since deep chiseling], the current DRAINMOD model assumes that the Green-Ampt equation (Equation 5-1) parameters remain constant irrespective of tillage operation carried out (Skaggs, 1978) and the weathering effects thereof. Also in the current DRAINMD, the maximum depression storage (STMAX) is assumed to be evenly distributed over the entire farm field and it is further assumed constant irrespective of factors that may affect depression storage depth such as time, climatic conditions, or tillage operations (Skaggs, 1978). This is unfortunate because in practice, K_s and other soil hydraulic properties and STMAX do vary with farm management practices and it is therefore important to consider such management-related sources of variability in modeling (van Es et al., 1999).

5.1.1 Project Goals

A. To write and incorporate into DRAINMOD a dynamic K_s subroutine by

1. Developing a theoretical/mathematical equation.
2. Using field vertical saturated hydraulic conductivity data measured after deep chiseling a Commerce silt loam soil to calibrate the mathematical K_s equation.
3. Coding the mathematical K_s equation within DRAINMOD model thereby developing the modified DRAINMOD-K_s model.

B. To write and incorporate into DRAINMOD a dynamic STMAX subroutine by

1. Developing a theoretical/mathematical equation.
2. Using data generated from Gayle and Skaggs (1978) work to calibrate the dynamic mathematical STMAX model that varies with time since deep chiseling.

3. Coding the mathematical STMAX equation within the current DRAINMOD model thereby developing the modified DRAINMOD-STMAX.

C. To perform a sensitivity analysis on K_s and STMAX parameters using the modified DRAINMOD-K_s and DRAINMOD-STMAX models respectively.

5.2 Materials and Methods

5.2.1 Current DRAINMOD Model and the Desired K_s and STMAX Changes

Appendix A shows a general flowchart for the current DRAINMOD model, in which vertical saturated hydraulic conductivity is assumed constant. The dotted line sections show the locations where changes were to be made to the original DRAINMOD model to incorporate the rainfall intensity and deep chiseling effects. A general flow chart of the changes made to include the deep chiseling effects (includes a dynamic vertical saturated hydraulic conductivity (K_s) subroutine, a dynamic maximum surface depressional storage (STMAX) subroutine) are shown in Figure 5-1. Figure 5-1 further indicates the rainfall intensity problem that was noted completed in chapter 3. The equation, calibration, algorithm, subroutine and validation of the dynamic K_s and STMAX subroutines are discussed in the next sections.

5.2.2 K_s and STMAX Model Development

5.2.2.1 Vertical Saturated Hydraulic Conductivity (K_s) Model Development

Tillage operations increase infiltration and reduce surface runoff (Barisas et al., 1978; Ankey et al., 1995; van Es et al., 1999; Kincaid, 2002) by increasing the vertical component of saturated hydraulic conductivity (K) of the top and adjacent layers of soil (Kincaid, 2002). Unfortunately, the benefits of deep chiseling and other tillage operations in increasing K and hence infiltration are only temporary because the soil surface seal

(Martinez-Gamino, 1994; Slattery and Bryan, 1994; Assouline and Mualem, 2002) and soil compaction increases gradually to the previous condition as the fine particles fill the soil pore spaces after subsequent rainfall events (Allen and Musick, 2001; Rao et al., 1998; Kim and Chung, 1994).

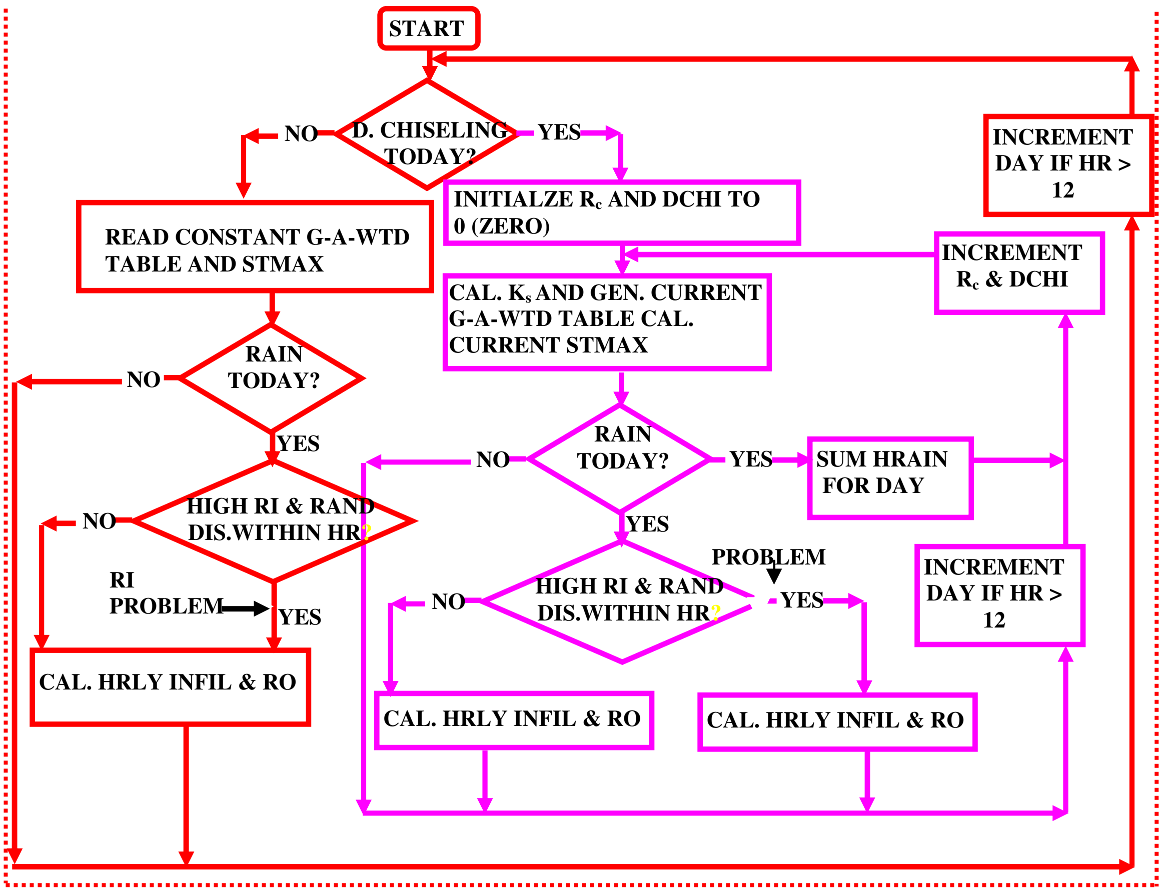


Figure 5-1. A general flow chart of deep chiseling effects modifications made

The impact of high-energy raindrops breaks up the surface soil clumps into fine aggregates, which fill the soil pores and form a surface seal (Haan et al., 1994). The soil surface seal is compacted by further raindrops. Upon drying, the cementing agents in clays form and bind soil particles together forming a continuous sheet (crust) on the soil surface (Martinez-Gamino, 1994). Therefore there is a gradual decrease in saturated hydraulic conductivity as the surface seal reforms to its previous condition. The main cementing agents in soils are silica in semiarid zones, sesquioxides in subtropical zones, and organic matter in both cases (Martinez-Gamino, 1994). Other cementing agents include amorphous silicate (SiO_2), and Si-Fe complexes (Chartres et al., 1990). Several field studies support soil surface sealing theory.

Kim and Chung (1994) found that average saturated hydraulic conductivity on a tilled a sandy loam soil layer gradually decreased exponentially as a function of cumulative rainfall energy after tillage. According to Rao et al. (1998), the decline in infiltration rate since tillage on an Alfisol was found to have an exponential relationship with cumulative rainfall since tillage. Allen and Musick (2001) found that deep ripping increased infiltration on a clay loam soil (Torrertic Paleustoll) by 26 to 29% immediately after primary tillage but the benefit of ripping was lost because of the subsequent furrow traffic and soil consolidation from irrigation and rainfall.

Therefore, based on the surface sealing research by Martinez-Gamino (1994), Slattery and Bryan (1994) and Assouline and Mualem (2002) and the field findings by Allen and Musick (2001), Rao et al. (1998b), and Kim and Chung (1994), it was hypothesized that vertical saturated hydraulic conductivity decreases exponentially with cumulative rainfall after deep chiseling from a maximum value to a steady state (final) value as expressed by Equation 5-1 and shown by Figure 5-2.

$$K_{st} = K_{sf} + (K_{si}-K_{sf}) \exp(-aR_c) \tag{5-1}$$

where K_{st} is vertical saturated hydraulic conductivity at time t (cm h^{-1}), K_{si} is vertical saturated hydraulic conductivity immediately following chiseling (cm h^{-1}), K_{sf} is asymptotical final infiltration rate (cm h^{-1}), R_c is the cumulative rainfall since chiseling (cm) , and a is a constant dependent on the type of soil and type of tillage practice (cm^{-1}).

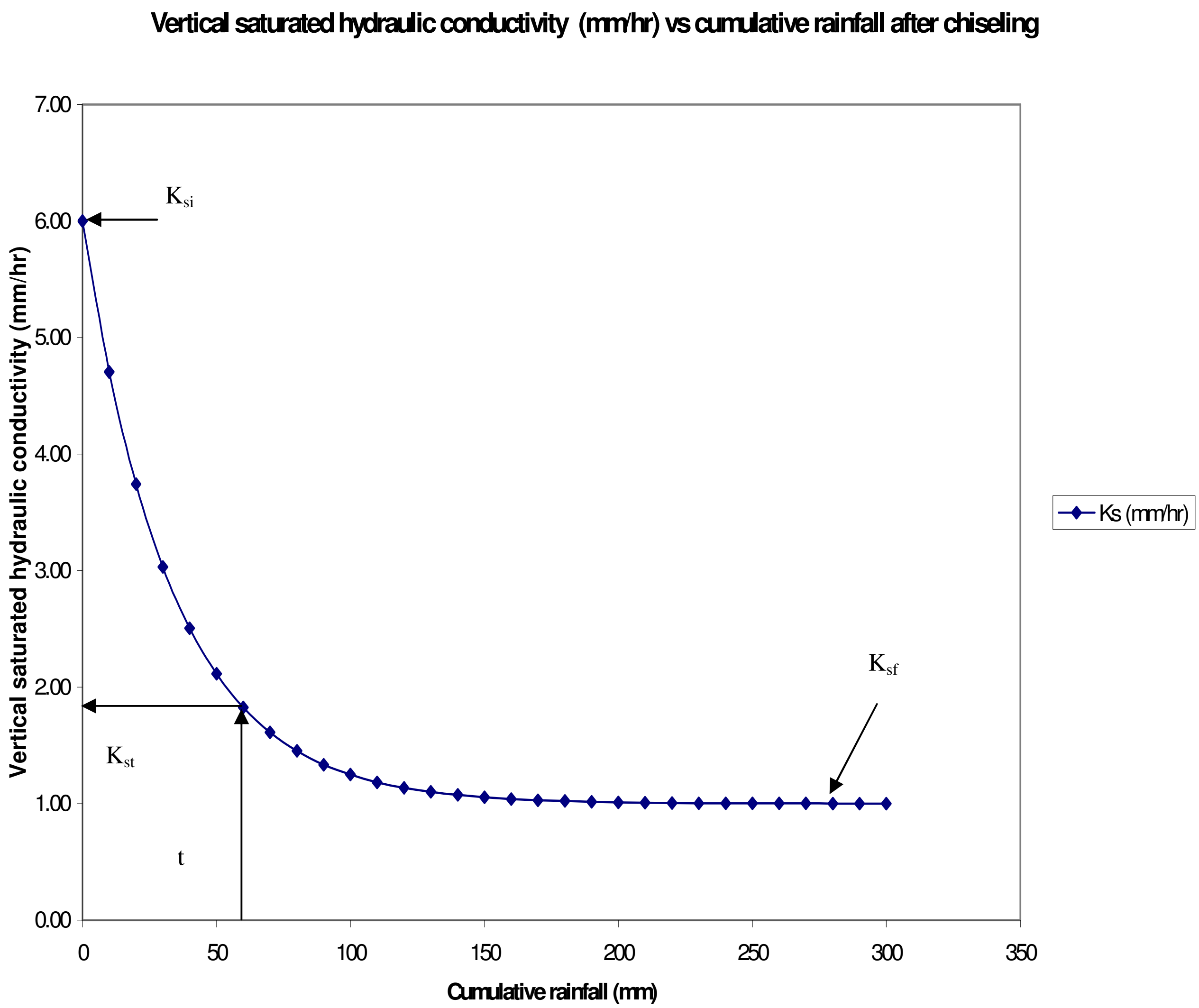


Figure 5-2. Hypothetical exponential decrease in soil vertical saturated hydraulic conductivity due to the reformation of a surface restrictive layer [Equation 5-1].

5.2.2.2. Maximum Surface Depressional Storage (STMAX) Model Development

Rainfall or irrigation water infiltration and runoff are influenced in part by depressional storage (Huang and Bradford, 1990). However, depressional storage is usually difficult to measure and is usually estimated from some surface roughness index (Onstad, 1984; Huang and Bradford, 1990; Kamphorst et al., 2000; Guzha, 2004).

Models that have been used to calculate maximum surface depressional storage include those by Moore and Larson (1979), Onstad (1984) and Guzha (2004). Moore and Larson (1979) developed a distributed model for estimating surface storage and runoff amounts for a plot from grid elevations. However this model does not show trends depending on either the amount of rainfall over time or over the tillage and farming operations. Onstad (1984) developed a depressional storage model based on the random roughness and slope of the depressions. Generally depressional storage decreases with decreasing random roughness and increasing slope steepness (Onstad, 1984). However, there is no data that shows how random roughness and slope steepness vary with farming operations or weathering effects.

Therefore this research used surface depressional measurements for clay loam soil conducted by Gayle and Skaggs (1978) and explained in Chapter two because this soil is similar to the top layer of Commerce silt loam soil at the research location (Kornecki and Fouss, 2001). Figure 2-9 of chapter two shows the annual variation of micro-storage for clay loam soil, which includes representative farming practices throughout the year. Based on the graph a decreasing exponential STMAX model, depending only on the number of days after deep chiseling a Commerce silt loam in fall or spring, was hypothesized (Equation 5-2).

$$MAXST = MAXSTF + (MAXSTI - MASXSTF)*EXP(-Amaxs*DCHI) \quad (5\text{-}2)$$

where MAXST is the current maximum depressional storage (cm) DCHI days after deep chiseling a Commerce silt loam soil, MAXSTF is the final maximum depressional storage (cm), MAXSTI is the initial maximum depressional storage (cm) and Amaxs is the model exponent which depends on farm operations and the type of soil (day^{-1}).

5.2.3. Model Calibration

5.2.3.1. Dynamic K_s Model Calibration

From the results reported in chapter four, vertical saturated hydraulic conductivity was significantly higher (p-value = 0.032) on a deep chiseled plot than the plot that was not chiseled. Although there was no clear pattern of the variation of field vertical saturated hydraulic conductivity (K) with cumulative rainfall since deep chiseling, the information gained was useful in giving an idea of the vertical saturated hydraulic conductivity range for the top layer of a Commerce silt loam soil.

Using the data collected, a graph of vertical saturated hydraulic conductivity versus cumulative rainfall since deep chiseling was drawn. An approximate exponential trend-line, the dark line in Figure 5-3, was drawn and extrapolated to determine the "true" initial vertical saturated hydraulic conductivity right after deep chiseling rather than the first K_s value measured on April 2nd 2004 after 24.7 cm of rainfall since deep chiseling. Approximate data was generated from the exponential trend-line and used to determine the required parameters for the dynamic K_s model (Equation 5-1) using nonlinear regression (SAS Institute Inc., 1999). The values of K_s used were 1/3 of the measured vertical saturated hydraulic conductivity (K) because of the entrapped air (Reynolds and Elrick, 1986).

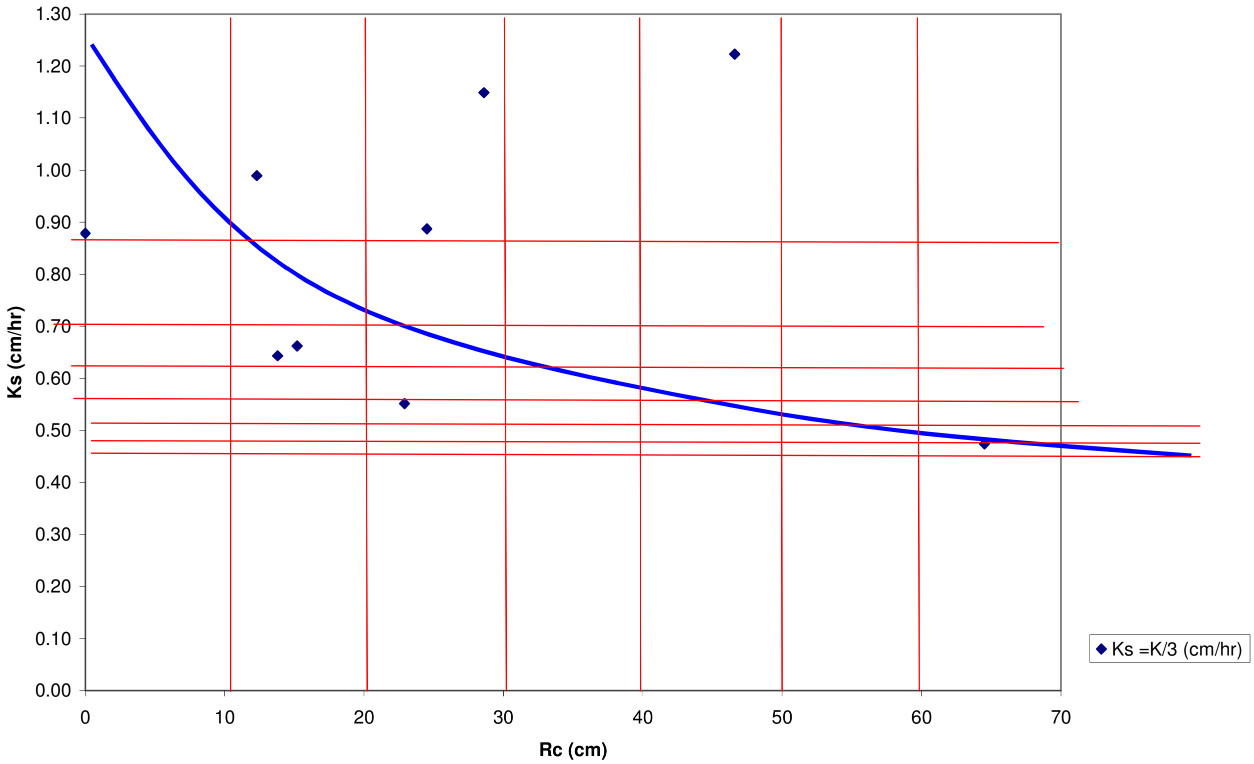


Figure 5-3. A graph of cumulative rainfall since deep chiseling (R_c) versus K_s =1/3 K (Measured field vertical saturated hydraulic conductivity) for Ben Hur

5.2.3.2. Dynamic STMAX Model Calibration

This model was calibrated using data collected by Gayle and Skaggs (1978) and approximately modified to fit deep chiseling tillage operation on Commerce silt loam soils. An approximate exponential trend line was drawn across Figure 2-9 in chapter two and data was generated and used to determine the required parameters for the dynamic STMAX model (Equation 5-2) using SAS nonlinear regression (SAS Institute Inc., 1999). Initial maximum surface depressional storage (MAXSTI) was determined using a maximum depressional storage model developed by Onstad (1984). This model is written as:

$$Sd = 0.112\ Rr + 0.031\ Rr^2 - 0.012 Rr.S \qquad (5\text{-}3)$$

where Sd is the maximum depressional storage (cm), Rr is random roughness (cm) and S is the slope steepness (%). According to RUSLE (1997), Rr for chisel with twisted shovel, disk with heavy plowing and moldboard plow is 4.826 cm. The slope steepness at the research location, USDA-ARS Ben Hur Research location, was 0.2% (Fouss and Willis, 1990). Substituting the values for these parameters into Equation 5-3 resulted in a MAXSTI value of 1.25 cm.

5.2.4 Dynamic K_s Model Algorithm

Unlike the soils in the Midwest where the top soil layer is the most conductive followed by less conductive layers underneath, the top layer of the Commerce silt loam soil is the least conductive layer because of the high surface clay content, about 27% (Kornecki and Fouss, 2001). According to Rogers et al. (1991) saturated hydraulic conductivity for the Commerce silt loam soil increases with depth for depths up to 1.5 m deep and then decreases with depth to the deeper soil layers. Therefore, the top/surface soil layer is the limiting layer for water infiltration, in other words, it does not matter how conductive the lower layers are, if the surface layer allows water into the soil at a certain rate, that rate is the limiting water infiltration rate.

Saturated hydraulic conductivity (K) values at different water table depths of Commerce silt loam soil is given in Table 5-1. Using the water table depths for the Green-Ampt equation parameters and assuming vertical saturated hydraulic conductivity (K_s) equal to 1/3 of the field measured vertical saturated hydraulic conductivity (K), the values of K_s were computed (Table 5-2). This value was used because, true saturated conditions rarely occur in the vadose zone except where restrictive layers result in perched water tables because of the entrapped air (Bouwer, 1966). The entrapped air prevents water moving in air-filled pores, which, consequently, may reduce the hydraulic conductivity measured in the field by as much as 50 percent compared to conditions when trapped air is not present (Reynolds and Elrick, 1986).

Table 5-1. Saturated hydraulic conductivity vs. water table depth, as determined by the auger hole method for the Commerce silt loam (from Fouss et al., 1987).

Depth in soil (cm)	Sat. hydr. Cond. (K)(cm/hr)
0.0 – 50.0	1.2
50.0 –120.0	4.0
120.0 – 141.5	0.1

Table 5-2. Vertical saturated hydraulic conductivity values used to generate Green-Ampt equation parameters for the Commerce silt loam soil.

Depth in soil (cm)	K (cm/hr)	K_s=K/3 (cm/hr)
0	1.2	0.40
30	1.2	0.40
60	4.0	1.33
120	4.0	1.33
150	0.1	0.03
500	0.1	0.03

However, because the top layer vertical saturated conductivity was the limiting layer for soil water infiltration, Fouss et al. (1987) generated the parameters for the Green-Ampt infiltration equation for different water table depths based only on the K_s for the top layer (Table 5-3). The Green-Ampt parameters in Table 5-3 used in the current DRAINMOD model for the Commerce silt loam soil are assumed constant irrespective of farm management operations like tillage.

As discussed in section 5.2.2.1, tillage operations tend to increase vertical saturated hydraulic conductivity, attaining its maximum value immediately following tillage and decreasing gradually to the value just before the tillage operation (Kim and Chung, 1994). Therefore, three possible Green-Ampt parameter table-scenarios were considered after vertical saturated hydraulic conductivity (K_s) was allowed to vary exponentially depending on cumulative rainfall after deep chiseling a Commerce silt loam (Equation 5-1). Before each scenario is described determination of other parameters used to evaluate the Green-Ampt infiltration equation parameters (A, B) is briefly explained.

Table 5-3. Parameters for the Green-Ampt infiltration equation for various water table depths at the start of rainfall [Commerce silt loam] (from Fouss et al., 1987).

Depth (cm)	$A = K_sMS_{av}(cm^2/hr)$	$B = K_s$ (cm/hr)
0	0.0	0.4
30	0.4	0.4
60	0.8	0.4
120	1.12	0.4
150	1.76	0.4
500	1.76	0.4

Given the values of A and B in Table 5-3 and assuming that M and S_{av} at each water table depth remain constant, the product of M and S_{av} for water table was evaluated (Table 5-4).

Table 5-4. Product of M and S_{av} for various water table depths for a Commerce silt loam calculated from data in Table 5-3 (from Fouss et al., 1987).

Depth (cm)	MS_{av}(cm)
0	0.00
30	1.00
60	2.00
120	2.80
150	4.40
500	4.40

5.2.4.1 Scenario 1 – Right After Deep Chiseling

This scenario occurs immediately after deep chiseling as long as K_s for the top soil layer (0-30 cm) remains greater than or equal to K_s for the next layer (1.33 cm/hr) (Table 5-5).

Table 5-5. Green-Ampt infiltration equation parameters when the topsoil layer is more conductive than 1.33 cm/hr - scenario 1.

WTD (cm)	A (cm^2/hr)	B (cm/hr)
0	0.00	$K_{sf}+(K_{si}-K_{sf})exp(-aR_c)$
30	$K_{sf}+(K_{si}-K_{sf})exp(-aR_c)$	$K_{sf}+(K_{si}-K_{sf})exp(-aR_c)$
60	1.33*2.00	1.33
120	1.33*2.80	1.33
150	0.03*4.40	0.03
500	0.03*4.40	0.03

5.2.4.2 Scenario 2 –K_s between Layer 2 and Pre-deep Chisel Value

This is the case when vertical saturated hydraulic conductivity for the top soil layer (0-30 cm) is less than the next layer's K_s (1.33 cm/hr) but greater than K_s for the top soil before deep chiseling (0.40 cm/hr) (Table 5-6). In this case K_s for the topsoil layer is the limiting K_s.

Table 5-6. Green-Ampt infiltration equation parameters when the topsoil K_s is equal or less than 1.33 cm/hr but greater than 0.4 cm/hr- scenario 2.

WTD (cm)	A (cm^2/hr)	B (cm/hr)
0	0.00	$K_{sf}+(K_{si}-K_{sf})exp(-aR_c)$
30	$K_{sf}+(K_{si}-K_{sf})exp(-aR_c)$	$K_{sf}+(K_{si}-K_{sf})exp(-aR_c)$
60	$(K_{sf}+(K_{si}-K_{sf})exp(-aR_c))$*2.00	$K_{sf}+(K_{si}-K_{sf})exp(-aR_c)$
120	$(K_{sf}+(K_{si}-K_{sf})exp(-aR_c))$*2.80	$K_{sf}+(K_{si}-K_{sf})exp(-aR_c)$
150	$(K_{sf}+(K_{si}-K_{sf})exp(-aR_c))$*4.40	$K_{sf}+(K_{si}-K_{sf})exp(-aR_c)$
500	$(K_{sf}+(K_{si}-K_{sf})exp(-aR_c))$*4.40	$K_{sf}+(K_{si}-K_{sf})exp(-aR_c)$

5.2.4.3 Scenario 3 – K_s Equals to Value before Deep Chiseling

This is the case when vertical saturated hydraulic conductivity for the topsoil layer (0-30 cm) is equal or less than the relatively steady K_s for the topsoil before deep chiseling (0.40 cm/hr) (Table 5-7). Just like in scenario 2, K_s for the topsoil layer is the limiting K_s.

Table 5-7. Green-Ampt infiltration equation parameters when the topsoil K_s is equal or less than 0.4 cm/hr- scenario 3.

WTD (cm)	A (cm^2/hr)	B (cm/hr)
0	0.0	0.4
30	0.4	0.4
60	0.8	0.4
120	1.12	0.4
150	1.76	0.4
500	1.76	0.4

5.2.5 Incorporation of K_s and STMAX Models into DRAINMOD

5.2.5.1 Dynamic K_s Subroutine within DRAINMOD - DRAINMOD-K_s Model

K_s input parameters, generated after calibration, were stored in the modified General input file (Benhurdchis.GEN) and read only if the flag is 1 (Appendix C). When the flag is zero it indicates that deep chiseling was not done and therefore the subroutine is not called whereas if the flag is 1 it means that deep chiseling was done and therefore K_s parameters are read. Cumulative rainfall since deep chiseling a Commerce silt loam soil is used to compute the current K_s for the topsoil layer (Equation 5-1), which is then used to generate the current Green-Ampt parameters for the various water table depths. The current Green-Ampt parameters were then used to calculate infiltration if rainfall occurs on that particular day. The subroutine algorithm is shown in Figure 5-4.

The subroutine code (Appendix D) was written using Microsoft FORTRAN PowerStation version 4.0 (Microsoft, 1995) and incorporated into the current DRAINMOD model. The K_s modified DRAINMOD model (DRAINMOD-K_s model) was run and the predicted infiltration and surface runoff output, after deep chiseling operation, was recorded.

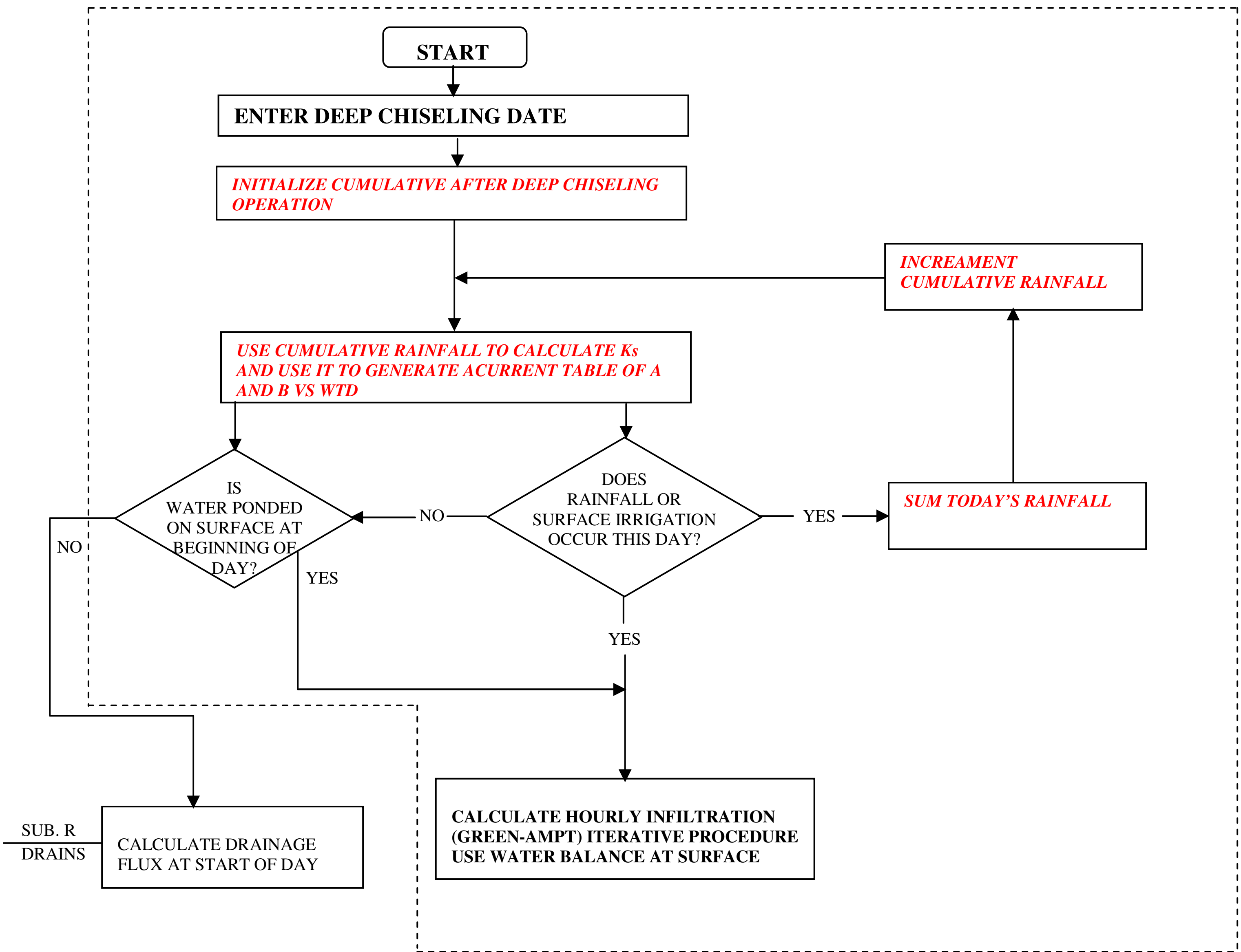


Figure 5-4. An abbreviated flow chart for the dynamic K_s subroutine within DRAINMOD

5.2.5.2 Dynamic STMAX Subroutine within DRAINMOD - DRAINMOD-STMAX Model

STMAX input parameters, generated after calibration, were also stored in the modified general input file (Benhurdchis.GEN) and read only if the flag (0 or 1) is 1 (Appendix C). When the flag is zero it indicates that deep chiseling was not done and therefore the subroutine is not activated whereas if the flag is 1 deep chiseling was done and the subroutine is activated to calculate and use the current STMAX. The number of days since deep chiseling a Commerce silt loam soil was used to compute the current STMAX (Equation 5-2), which was then used to calculate infiltration during a rain event. The algorithm for this subroutine is given in Figure 5-5.

The subroutine code (Appendix E) was written using Microsoft FORTRAN PowerStation version 4.0 (Microsoft, 1995) and incorporated into the current DRAINMOD model. The STMAX modified DRAINMOD model (DRAINMOD-STMAX model) was run and the predicted infiltration and surface runoff output, after deep chiseling operation, was recorded.

5.3. DRAINMOD-K_s and DRAINMOD-STMAX Parameter Sensitivity Analysis

A sensitivity analysis is the process of varying model input parameters over a reasonable range (range of uncertainty in values of model parameters) and observing the relative change in model response. Sensitivity analysis is carried out to demonstrate the sensitivity of the model simulations to uncertainty in values of model input data.

The relationship proposed by McCuen (1973) and described by Thomas and Beasley (1986) was used to determine the relative sensitivity of the parameters in these two models.

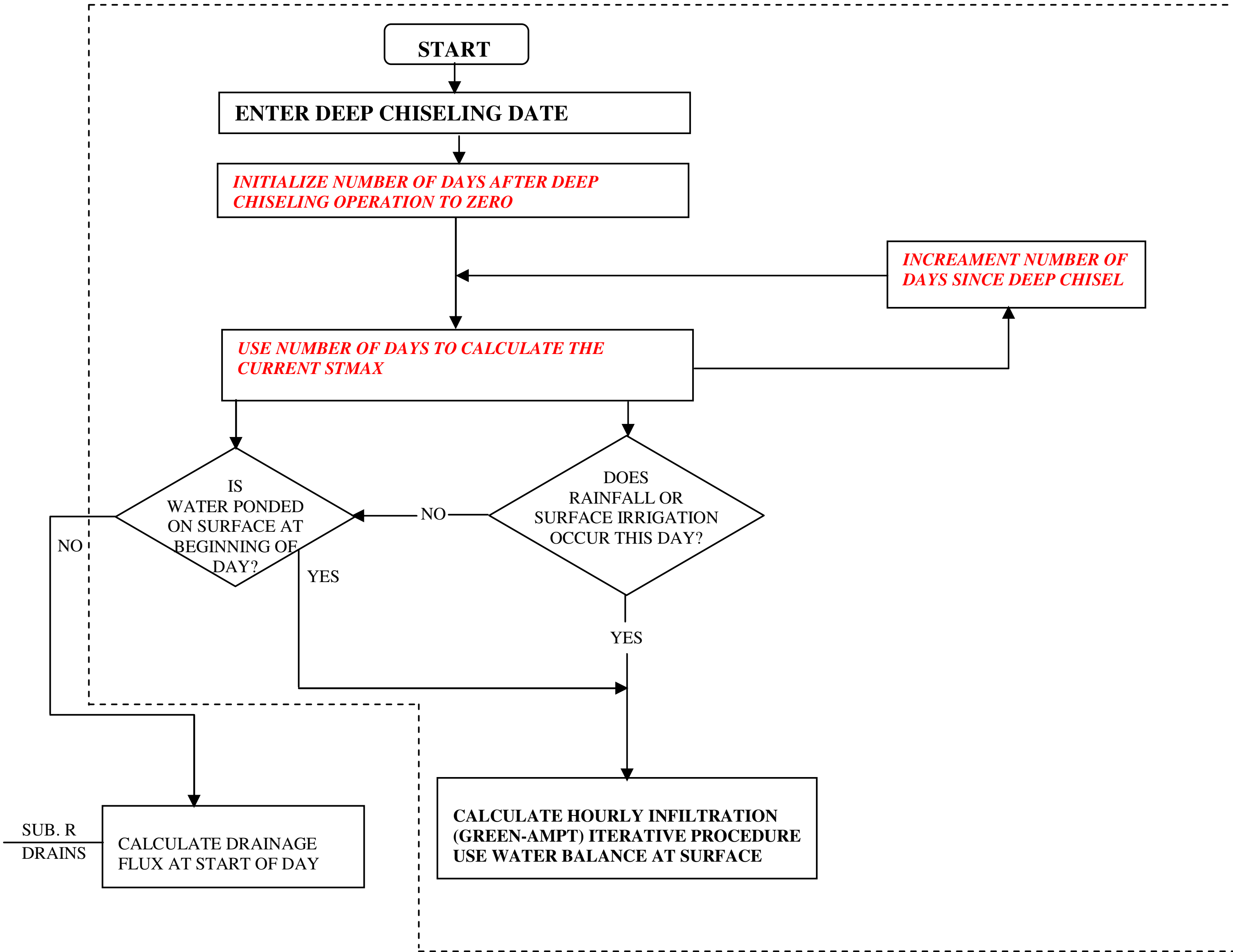


Figure 5-5. An abbreviated flow chart for the dynamic STMAX subroutine within the DRAINMOD model

This relationship was:

$$R_s = \frac{\Delta F_o / F_o}{\Delta F_i / F_i} \tag{5-4}$$

where R_s is the rrelative sensitivity, ΔF_o is the change in the output, F_o is the base output, ΔF_i is the change in the parameter value and F_i is the base parameter value.

The parameters whose sensitivities were calculated are the initial vertical saturated hydraulic conductivity (K_{si}) and initial maximum depressional storage depth (MAXSTI) because the values of these parameters vary depending on the type of tillage operation. The final vertical saturated hydraulic conductivity (K_{sf}) and the final maximum depressional storage depth (MAXSTF) for a given soil type were assumed constant and hence they were not considered in this analysis. Maximum K_{si} was taken 6.0 cm/hr, a realistic value (Rao et al., 1998a) and the minimum K_{si} was taken as 1.0 cm/hr, which is half the value (2.0 cm/hr) determined from the field experiments as explained in section 5.2.3.1 of this chapter. The maximum MAXSTI was 1.25 cm MAXSTI (used in model), with other possible values being a minimum of 0.65 (half the base value) and mid value of 0.95 cm. The effect of each of these parameters (K_{si} and MAXSTI) on total runoff, infiltration and drainage were determined by changing the parameters running model simulations for two periods, between September 28, 1995 and November 21, 1996 and between November 22, 1996 and November 22, 1997 when deep chiseling was carried out in Ben Hur. The results from the simulations are presented in the results and discussion section below.

5.4. Results and Discussion

5.4.1 Modified DRAINMOD Models Output Files

Output files that automatically had project names with an extension .CHK for the DRAINMOD-K_s model (Table 5-8) and an extension .CHS for the DRAINMOD-STMAX model (Table 5-9) were generated and used to check whether these modified DRAINMOD models were calculating the correct parameter values. Table 5-8 shows an excerpt of the dynamic vertical saturated hydraulic conductivity (K_s) subroutine output with zero cumulative rainfall used to determine the initial K_s and Green-Ampt parameter table. Daily rainfall was recorded and used to increment cumulative rainfall. Cumulative rainfall was used to compute the current K_s, which was then used to generate the current Green-Ampt parameter table. The current water table depth was included in this output file and used, by linear interpolation, to determine the correct Green-Ampt parameters (A and B) to be used to calculate infiltration and hence surface runoff. All three scenarios, depending on the stage of soil surface seal formation, were recorded.

Table 5-9 shows an excerpt of the dynamic maximum surface depressional storage (STMAX) subroutine output with zero days to determine the initial STMAX on deep chiseling date. Number of days after deep chiseling was incremented at the end of each day and used to calculate the current STMAX, which was then used to calculate infiltration and hence surface runoff. Output data generated by both the modified DRAINMOD-K_s and DRAINMOD-STMAX could be used to determine the current stage of surface seal reformation. This would be useful in determining when to start a new deep chiseling operation.

Table 5-8. Excerpt of DRAINMOD-K_s model output file – Test8.CHK

```
          *             DRAINMOD-Ks                                  *
          * Copyright 1980-99 North Carolina State University *
BENHUR - CONVENTIONAL DRAINAGE (05-05-2003)
1994-2000 DRAINMOD-Ks
***********************************************************************
Cum rainfall on chiseling day (cm)=     .00
TODAYS RAIN        CURRENT Ks
    (CM)            (CM/HR)
     .00             2.00
            CURRENT GREEN AMPT INFILTRATION PARAMETERS TABLE
                     W.T.D.         A          B
                      (CM)       (CM^2/HR)   (CM/HR)
                        .000        .000      2.000
                      30.000      2.000      2.000
                      60.000      2.660      1.330
                     120.000      3.720      1.330
                     150.000       .130       .030
                     500.000       .130       .030
                    1000.000       .130       .030
Current WTD    Interpol A    Interpol B
    (cm)        (cm^2/hr)      (cm/hr)
    111           3.56           1.33
Cum rainfall since chiseling (cm)=     .00
Cum rainfall since chiseling (cm)=   28.88
TODAYS RAIN        CURRENT Ks
    (CM)            (CM/HR)
    1.02             1.13
            CURRENT GREEN AMPT INFILTRATION PARAMETERS TABLE
                     W.T.D.         A          B
                      (CM)       (CM^2/HR)   (CM/HR)
                        .000        .000      1.130
                      30.000      1.130      1.130
                      60.000      2.260      1.130
                     120.000      3.170      1.130
                     150.000      4.980      1.130
                     500.000      4.980      1.130
                    1000.000      4.980      1.130
Current WTD    Interpol A    Interpol B
    (cm)        (cm^2/hr)      (cm/hr)
      0            .00            .00
Cum rainfall since chiseling (cm)=   29.90
Cum rainfall since chiseling (cm)=  175.29
TODAYS RAIN        CURRENT Ks
    (CM)            (CM/HR)
    7.90              .51
            CURRENT GREEN AMPT INFILTRATION PARAMETERS TABLE
                     W.T.D.         A          B
                      (CM)       (CM^2/HR)   (CM/HR)
                        .000        .000       .400
                      30.000       .400       .400
                      60.000       .800       .400
                     120.000      1.120       .400
                     150.000      1.760       .400
                     500.000      1.760       .400
                    1000.000      1.760       .400
```

Table 5-9. Excerpt of DRAINMOD-STMAX model output file – Test8.CHS

```
*                 DRAINMOD-STMAX                    *
* Copyright 1980-99 North Carolina State University *
   BENHUR - CONVENTIONAL DRAINAGE (05-05-2003)
           1994-2000 DRAINMOD-STMAX
***************************************************************************
----------RUN STATISTICS ----------       time:  8/ 6/2004  @  3:59
                 input file:   Test8.prj
***************************************************************************
         No. of Days Since Chiseling        STMAXC (cm)
         ************************           **********
                    0                          1.25
                    1                          1.24
                    2                          1.22
                    3                          1.21
                    4                          1.20
                    .                           .
                    .                           .
                    .                           .
                  141                           .31
                  142                           .31
                  143                           .31
                  144                           .30
                  145                           .30
                    .                           .
                    .                           .
                    .                           .
                  281                           .14
                  282                           .14
                  283                           .14
                  284                           .14
                  285                           .14
                    .                           .
                    .                           .
                    .                           .
                  416                           .11
                  417                           .11
                  418                           .11
                  419                           .11
                  420                           .11
```

5.4.2 DRAINMOD-K_s and DRAINMOD-STMAX Parameter Sensitivity Analysis

The simulation output data used in parameter sensitivity analysis is presented in Table 5-10. These outputs were used to calculate (Equation 5-4) relative sensitivity of each parameter during each time period. The computed relative sensitivity values for each parameter are given in Table 5-11. The positive values indicate increases and negative values indicate decreases in the outputs (total runoff, total infiltration, total drainage). The results depend on the site and therefore, they may differ from one location to another.

Table 5-10. DRAINMOD-K_s and DRAINMOD-STMAX simulation output. Where TRO is total runoff (cm), TF is total infiltration (cm) and TD is total drainage (cm).

Model	Parameter name	Parameter value	Time period					
			9/28/95 – 11/21/96			11/22/96 – 11/22/97		
			TRO	TF	TD	TRO	TF	TD
DRAINMOD-K_s	K_{si}, cm/hr	1.0	55.14	132.49	68.00	39.22	145.07	77.97
		2.0	52.76	134.87	70.23	36.59	147.67	80.58
		6.0	49.98	137.67	72.68	33.64	150.65	83.37
DRAINMOD-STMAX	MAXSTI, cm	0.65	57.71	129.95	65.96	39.99	144.31	77.20
		0.95	56.31	131.33	67.30	39.41	144.85	77.77
		1.25	54.99	132.65	68.57	38.65	145.61	78.53

Table 5-11. Relative sensitivity of output to changes in parameter values. Where TRO is total runoff (cm), TF is total infiltration (cm) and TD is total drainage (cm).

Model	Parameter name	Parameter value	Relative sensitivity					
			9/28/95 – 11/21/96			11/22/96 – 11/22/97		
			TRO	TF	TD	TRO	TF	TD
DRAINMOD-K_s	K_{si}, cm/hr	1.0 - 2.0	-0.043	0.018	0.033	-0.067	0.018	0.033
		2.0 – 6.0	-0.026	0.010	0.017	-0.040	0.010	0.017
DRAINMOD-STMAX	MAXSTI, cm	0.65 - 0.95	-0.053	0.023	0.044	-0.031	0.008	0.016
		0.95 –1.25	-0.053	0.032	0.060	-0.061	0.017	0.031

The results show that relative sensitivity of three outputs (TRO, TF,TD) varies from one time period to another. This variation could be due to different amount, intensity and distribution of rainfall from season to season. These results show that increasing K_{si} and MAXSTI slightly decreases total runoff, and increases total infiltration and total drainage.

The effect of changes in K_{si} and MAXSTI on the calculated daily runoff is illustrated in Figure 5-6, 5-7, 5- 8 and 5-9.

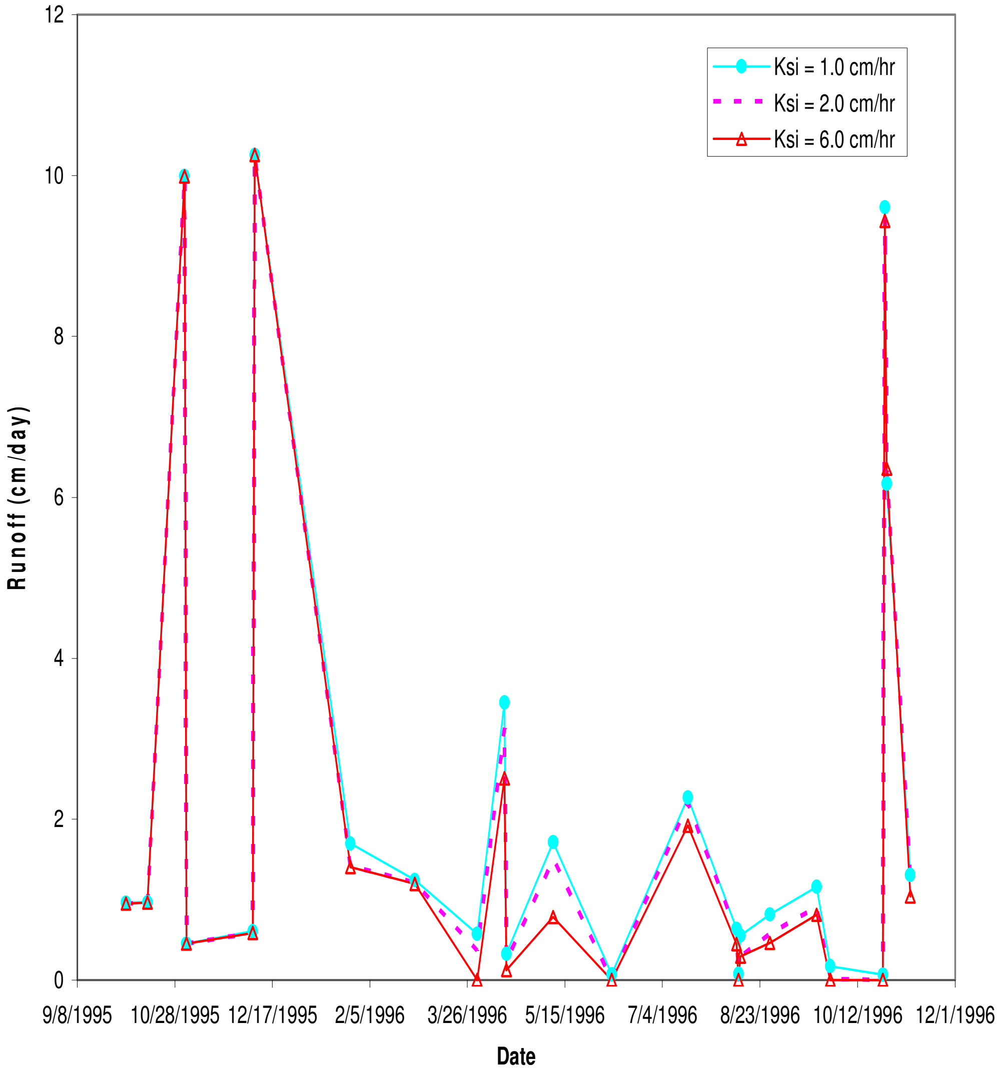


Figure 5-6. The effect of initial vertical saturated hydraulic conductivity (K_{si}) on daily runoff – 9/28/95 to 11/21/96

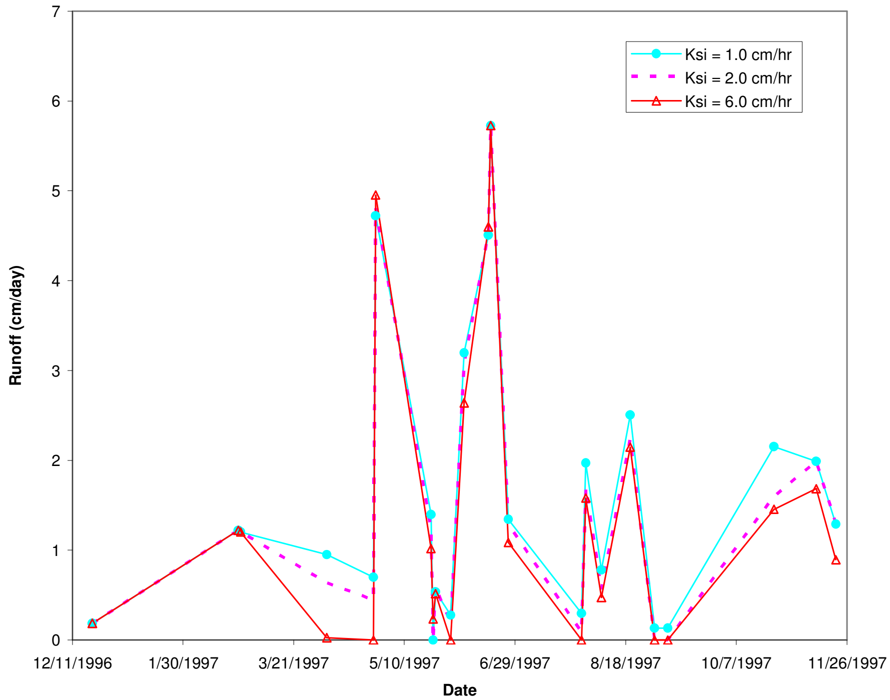


Figure 5-7. The effect of initial vertical saturated hydraulic conductivity (K_{si}) on daily runoff – 11/22/96 to 11/22/97

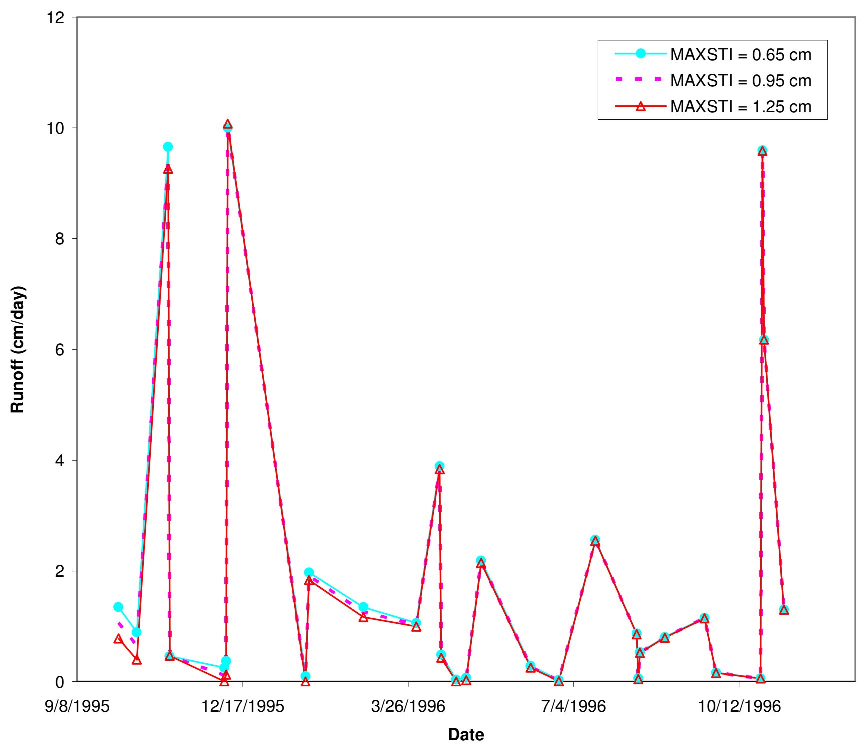


Figure 5-8. The effect of initial maximum depressional storage (MAXSTI) on daily runoff – 9/28/95 to 11/21/96

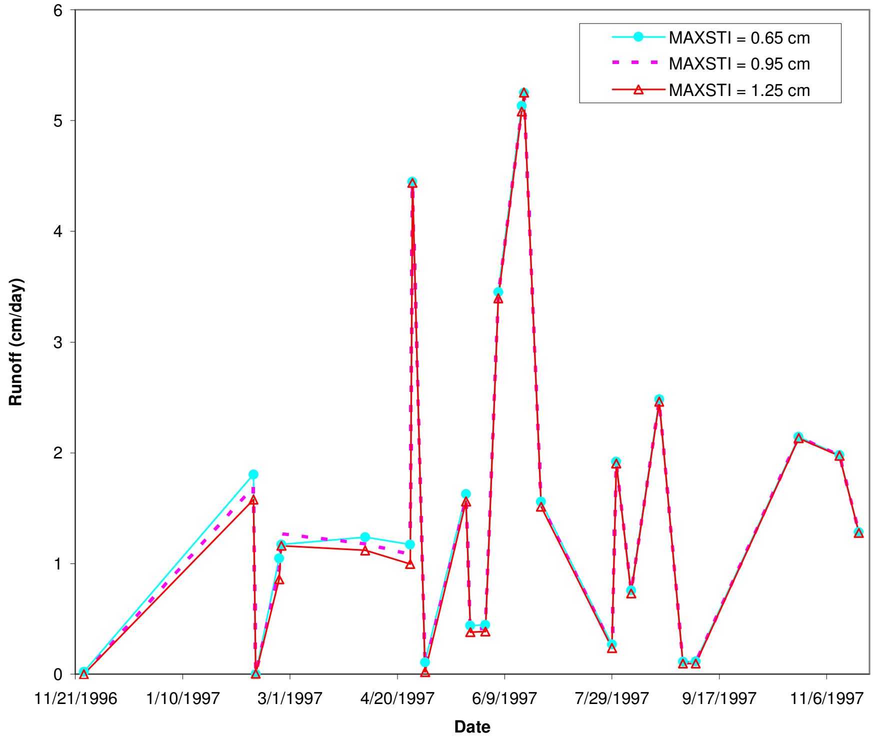


Figure 5-9. The effect of initial maximum depressional storage (MAXSTI) on daily runoff – 11/22/96 to 11/22/97

Generally, changes in K_{si} and MAXSTI do not cause large changes in the output daily surface runoff as shown the graphs above. However, an increase in K_{si} causes a significant decrease in daily runoff on some days (Figures 5-6 and 5-7) while the same increase does not cause a significant decrease in daily runoff. This observation could be due to the differences in rainfall intensities, with the greatest effect of K_{si} on daily runoff during high intensity rain events and least effect when the rainfall intensity is low. Changes in MAXSTI did not seem to change daily runoff much (Figure 5-8 and Figure 5-9) although an increase in MAXSTI decreased total runoff (Table 5-10). Although, the changes in the daily runoff due to changes in Ksi and MAXSTI are small, it is still important to determine accurately these parameters to ensure accurate model estimation.

5.5 Conclusions

Based on the theory of soil surface seal formation and past work a mathematical model was developed. Vertical saturated hydraulic conductivity decreases exponentially with cumulative rainfall after deep chiseling from a maximum value to a steady state (final) value as expressed by Equation 5-2 and shown by Figure 5-2. Using data measured after deep chiseling a Commerce silt loam, a southern alluvial soil, the equation parameters were determined. Initial vertical saturated hydraulic conductivity (K_{si}) was 2.0 cm/hr, final vertical saturated hydraulic conductivity (K_{sf}) was 0.50 cm/hr, and the exponent a, which depends on soil type, was 0.03 cm^{-1}. The model was then coded using Microsoft FORTRAN PowerStation version 4.0 (Microsoft Corporation, 1995) and incorporated into DRAINMOD.

Based on past research (Gayle and Skaggs, 1978; Onstad, 1984; Kincaid, 2002) a mathematical maximum surface depressional storage (STMAX) model was developed. STMAX was hypothesized to decrease exponentially, depending on the number of days after deep chiseling, from a maximum value to a steady state (final) value as expressed by Equation 6-1 and shown by Figure 6-1. Using data by Gayle and Skaggs (1978) that was adjusted for deep chiseling operation (RUSLE, 1997), equation parameters were determined. Initial maximum surface depressional storage (MAXSTI) was 1.25 cm, final maximum surface depressional storage (MAXSTF) was 0.10 cm, and the exponent Amaxs was 0.012 day^{-1}. This model was then coded using Microsoft FORTRAN PowerStation version 4.0 (Microsoft Corporation, 1995) and incorporated into DRAINMOD.

The sensitivity of the computed total runoff, total infiltration and total drainage to changes in K_{si} and MAXSTI shows that changes in these parameters do not cause large changes in the computed DRAINMOD components above. However, an increase in K_{si} causes a significant decrease in daily runoff on some days while the same increase does not cause a significant decrease in daily runoff. This observation could be due to the differences in rainfall intensities, with the greatest effect of K_{si} on daily runoff during high intensity rain events and least effect when the rainfall intensity is low. Changes in MAXSTI slightly changed the calculated daily runoff. Although, the changes in the daily runoff due to changes in K_{si} and MAXSTI are small, it is still important to determine accurately these parameters to ensure accurate model estimation.

CHAPTER SIX

COMPARISON OF SURFACE RUNOFF ESTIMATION BY THE ORIGINAL DRAINMOD MODEL AND BY THE MODIFIED DRAINMOD MODELS FOR A SOUTHERN ALLUVIAL SOIL

6.1 Introduction

Two out of three intended DRAINMOD model modifications were made. In chapter five the effect of deep chiseling on vertical saturated hydraulic conductivity (K_s) and maximum surface depressional storage (STMAX) were modeled and incorporated into the DRAINMOD model, as DRAINMOD-K_s and DRAINMOD-STMAX respectively, to increase the accuracy of its prediction of infiltration and runoff. The third modification, which involves modeling rainfall intensity using a five-minute rainfall increment, requires further work to complete and therefore was not considered in this chapter.

The primary objective of this study was to validate the original DRAINMOD, the DRAINOMD-K_s, the DRAINMOD-STMAX and the combined DRAINMOD-K_s-STMAX models and to determine by how much each individual and combined modified DRAINMOD models improved the accuracy of predicting infiltration and surface runoff relative to prediction by the original DRAINMOD model. The ultimate goal was to determine the DRAINMOD model modification/s that give/s the most accurate surface runoff and therefore infiltration predictions when a Commerce silt loam soil is deep chiseled.

6.1.1 Goals

A. To validate the Original DRAINMOD model and the modified DRAINMOD models using actual surface runoff measurements.

   1. Original DRAINMOD

2. Modified DRAINMOD-K_s

3. Modified DRAINMOD-STMAX

4. 2 & 3 together, DRAINMOD-K_s-STMAX

B. To determine by how much each of the modifications (2, 3, and 4) improved the Original DRAINMOD model prediction accuracy and thereby determine the model that gives the best surface runoff and hence infiltration prediction.

6.2. Materials and Methods

The first step was to validate the Original DRAINMOD model, the modified DRAINMOD-K_s, DRAINMOD-STMAX and the combined DRAINMOD-K_s-STMAX models using measured surface runoff from Ben Hur. Secondly using the Original DRAINMOD surface runoff prediction output as the reference, the surface runoff prediction accuracy improvement by each of the modified DRAINMOD-K_s, DRAINMOD-STMAX and the combined DRAINMOD-K_s-STMAX models were determined and ultimately the most accurate model selected.

6.2.1 Validation of Original DRAIMOD, DRAINMOD-K_s, DRAINMOD-STMAX and the Combined DRAINMOD-K_s-STMAX Models

Surface runoff data was collected at the research site and used to validate the Original DRAINMOD, DRAINMOD-Ks, DRAINMOD-STMAX and DRAINMOD-K_s-STMAX models at the research site. Previously surface runoff was collected in a shallow ditch on the down slope side of the plots, which routes the flow through an H-flume for measurement (Fouss and Willis, 1990). Currently surface runoff is collected in quarter drains across the plot on the sump end of the sump and routed through a 20 cm diameter PVC pipe collection unit fixed below the soil surface for measurement. The collection unit allows water in only one direction to prevent water backup during heavy storm events.

Measurement was accomplished using the STREAMLOG 800SL refrigerated sampler manufactured by American Sigma. Using a pressure transducer, which correlates flow with height of flow in the collection unit using the Manning's formula, a sample of 200 ml is collected for every 2,000 liters of flow. This fraction (1/10,000) of flow was automatically collected and preserved by refrigeration for nutrient and pesticide analysis. The data is easily downloaded from the 800SL sampler using an external model into a desktop PC.

There were few rain events with significant amount of rainfall to cause surface runoff during the research period (April – October 2003). During the few events that had significant amount of rainfall, the storms were so intense that there was runoff backup that caused the system to overestimate surface runoff, which made the data invalid. Therefore, the data collected between September 28, 1995 and November 21, 1996 and between November 22, 1996 and November 22, 1997 (when deep chiseling was done) was used to validate the original DRAINMOD and DRAINMOD-K_s-STMAX models using the Student's paired T-test (SAS Institute Inc., 1999), that is, blocking on the date to increase precision.

6.2.2 Comparisons of Surface Runoff Prediction by the Original DRAINMOD Model and by the Three DRAINMOD Modified Models

Some of the validation information for the original and each of the modified DRAINMOD models was used to compare how close to measured runoff the Original DRAINMOD, DRAINMOD-K_s, DRAINMOD-STMAX and DRAINMOD-K_s-STMAX model predictions were (Table 6-2). Using the Original DRAINMOD model runoff predictions as the reference, runoff prediction improvement by each of the modified DRAINMOD models was quantified.

6.3 Results and Discussion

6.3.1 Validation of the Original DRAINMOD, DRAINMOD-K_s, DRAINMOD-STMAX and DRAINMOD-K_s-STMAX Models

Predicted surface runoff for two periods, September 28, 1995 through November 21, 1996 and November 22, 1996 and November 22 1997 were computed and recorded (Appendix F). Included in Appendix F is the measured daily rainfall and surface runoff measurements for validation. It was observed that on some days, surface runoff measurements were higher than rainfall data and no runoff with as much as 13 cm or more rainfall recorded. A possible reason for measured runoff being higher than rainfall would be water backup during heavy rainfall events and a possible explanation for no runoff during heavy rainfall events would be due to datalogger problems. Data during such days was discarded and not used in the validation process. Therefore, it is important to note that the accuracy of measured runoff is not always correct.

The null hypothesis tested to validate all the DRAINMOD models was that the mean measured surface runoff (M) was equal to the mean predicted surface runoff (P). Between September 1995 and November 1996, the predicted runoff by the original DRAINMOD model was significantly different from the measured runoff (p-value = 0.03) whereas the predicted runoff by the modified DRAINMOD-STMAX, DRAINOD-K_s and the combined DRAINMOD-K_s-STMAX models were not significantly different (p-value = 0.35, 0.47 and 0. 65 respectively) as shown in Table 6-1. The total predicted runoff by the DRAINMOD-K_s-STMAX model (16.50 cm) was closest to the measured runoff (18.01 cm), followed by the total predicted runoff by the DRAINMOD-K_s (20.26

cm), and by the DRAINMOD-STMAX (21.54 cm) models respectively (Table 6-1). Between November 1996 and November 1997, the predicted runoff by the original DRAINMOD model and the modified DRAINMOD models were not significantly different from the measured runoff (Table 6-1). However, total runoff predicted by the modified DRAINMOD models was closer to the total measured runoff than the total runoff predicted by the original DRAINMOD model (33.86 cm), with total predicted runoff by the DRAINMOD-K_s-STMAX model (26.55 cm) being closest to the total measured runoff (21.98 cm), followed that by the DRAINMOD-K_s (28.49 cm) and the DRAINMOD-STMAX (30.61 cm) models respectively as before (Table 6-1).

Table 6-1. Model validation results: Where TM is total measured runoff, TP is total predicted runoff, df = 23 for 1995-1996 and df = 34 for 1996-1997 for the paired t-test

Model	**September 1995 –November 1996**			**November 1996 – November 1997**		
	Surface runoff (cm)		p-value	Surface runoff (cm)		p-value
	TM	TP		TM	TP	
ORIGINAL DRAINMOD	18.01	26.23	0.03	21.98	33.86	0.12
DRAINMD-STMAX	18.01	21.54	0.35	21.98	30.61	0.26
DRAINMOD-K_s	18.01	20.26	0.47	21.98	28.49	0.43
DRAINMOD-K_s-STMAX	18.01	16.50	0.65	21.98	26.55	0.57

Regression analysis was carried out between the predicted and measured daily and cumulative runoff to determine how well they correlated with each other. The results in Table 6-2 indicate that during the period September 1995 through November 1996, there was a good correlation (high R^2 values) between the predicted and measured runoff both for the daily (Figure 6-1) and cumulative runoff (Figure 6-2). During the same time period, DRAINMOD-K_s-STMAX had slightly better correlation ($R^2 = 0.98$ and $R^2 = 0.99$

respectively) between its daily and cumulative predicted runoff values and the measured values than the rest of the DRAINMOD models as shown in Figure 6-1 and Figure 6-2.

Table 6-2. Correlation between daily measured and predicted runoff (DMP) and between cumulative measured and predicted runoff (CMP)

Model	**Correlation (R^2)**			
	Sept. 1995 – Nov. 1996 (df=23)		Nov. 1996 – Nov. 1997 (df=34)	
	DMP	CMP	DMP	CMP
ORIGINAL DRAINMOD	0.93	0.97	0.38	0.96
DRAINMOD-STMAX	0.94	0.96	0.36	0.98
DRAINMOD-K_s	0.96	0.98	0.27	0.98
DRAINMOD-K_s-STMAX	0.98	0.99	0.31	0.98

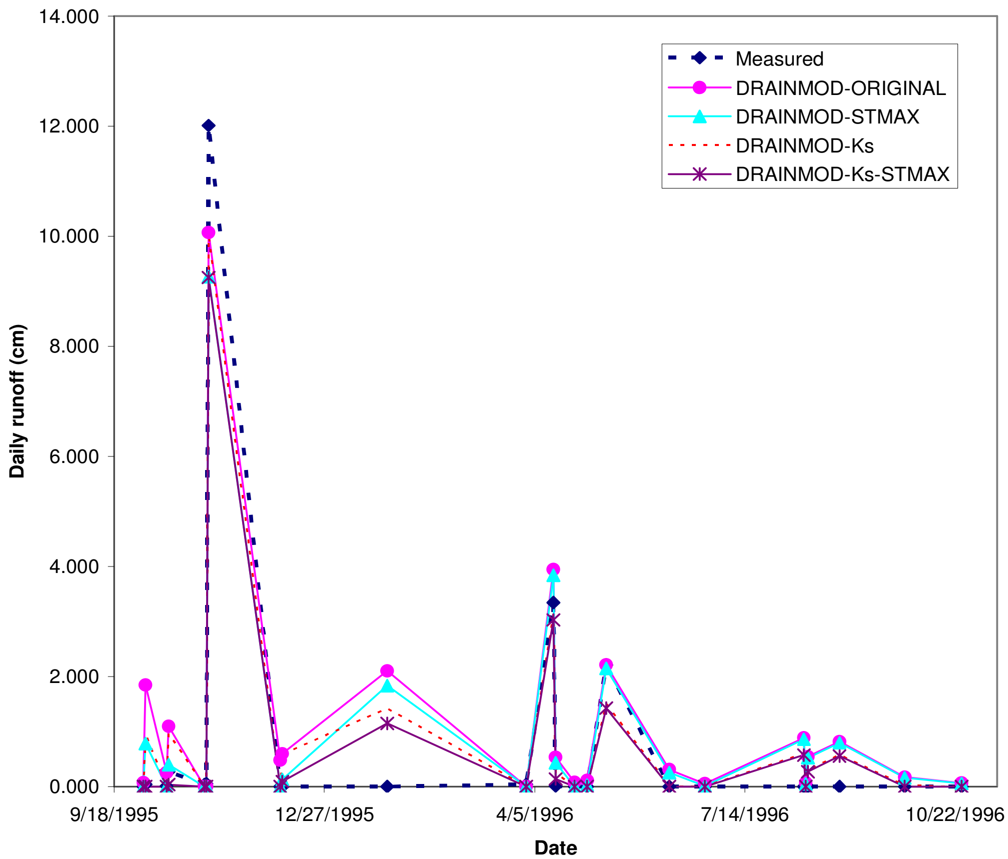


Figure 6-1. Measured and predicted daily runoff – September 1995 to November 1996

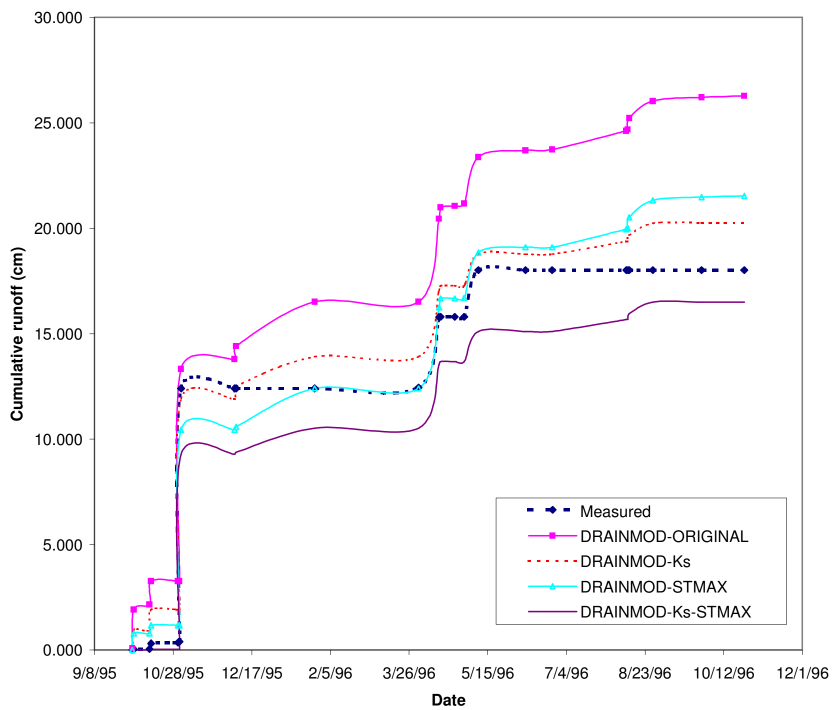


Figure 6-2. Measured and model predicted cumulative runoff – September 1995 to November 1996[ξ]

A possible reason for under-prediction by the DRAINMOD-K_s-STMAX model between September 1995 and November 1996 could be due to leveling/grading operation and addition of lime and nitrogen on the research plots done mid to end February 1996, which could have reduced both soil surface depressional storage and vertical saturated hydraulic conductivity of the top layer. Therefore, the decreasing exponential DRAINMOD-K_s-STMAX model computed and used higher vertical saturated hydraulic conductivity and maximum surface depressional storage values than the actual values after the plots had been graded.

[ξ] A possible reason for under-prediction by DRAINMOD-K_s-STMAX was leveling/grading done in Feb.

Between November 1996 and November 1997, there was not good correlation between predicted and measured runoff for the daily both for all the DRAINMOD models (Table 6-2) and as shown by Figure 6-3 but there was a good correlation between the measured and predicted cumulative runoff for all DRAINMOD models (Table 6-2) and as shown by Figure 6-4. There was no clear explanation for the poor correlation for the daily runoff data between November 1996 and November 1997 whereas the correlation between September 1995 and November 1996 being good. Differences in the rainfall patterns for different years in this region (Keim and Faiers, 1996; Bengtson and Carter, 2004) could explain the observed correlation differences. Therefore, further validation work is needed to determine the reliability of the modified DRAINMOD models under different weather conditions.

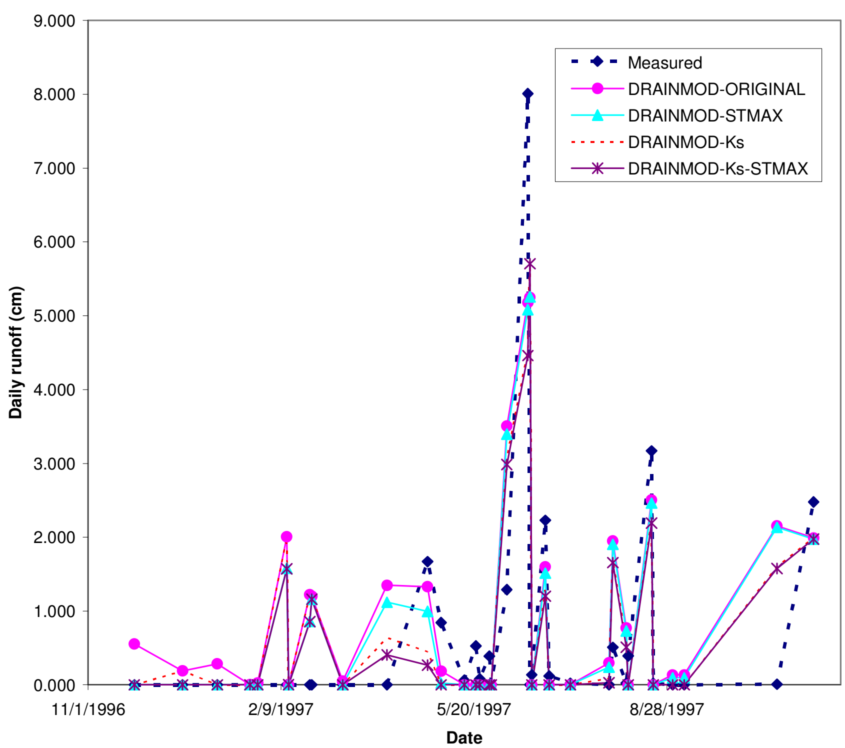


Figure 6-3. Measured and predicted daily runoff – November 1996 to November 1997

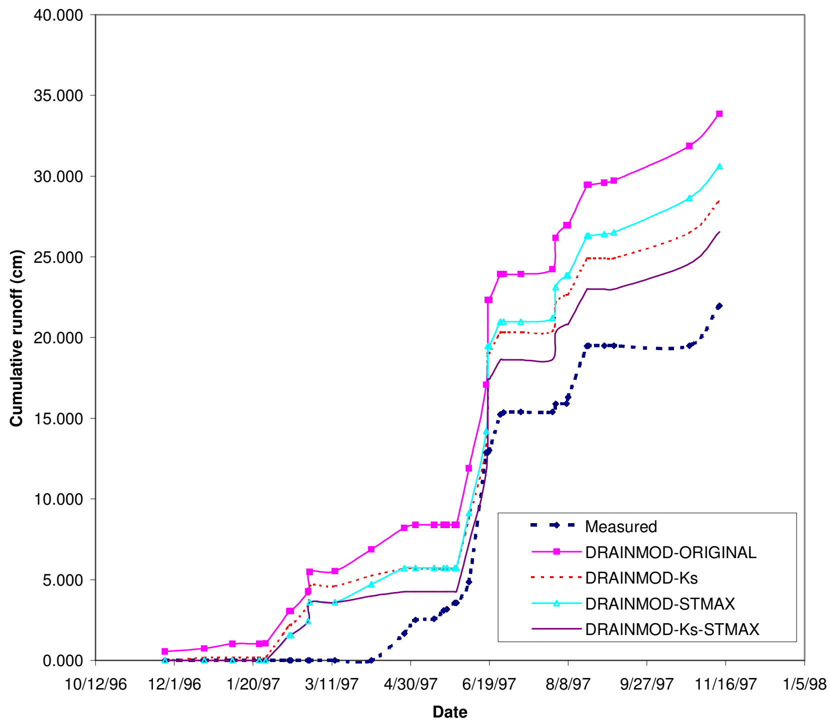


Figure 6-4. Measured and model predicted cumulative runoff – November 1996 to November 1997

6.3.2 Comparison of Runoff Prediction by the Original and the Three Modified DRAINMOD Models

First model diagnostics were carried out to determine by how much each DRAINMOD model over-predicted or under-predicted runoff compared with the actual rainfall and runoff data and the results were recorded in Table 6-3 and Table 6-4 for the periods between September 1995 and November 1996 and between November 1996 and November 1997 respectively. This information was used to determine the prediction accuracy of each one of these models. It is important to note, from Table 6-2 and Table 6-3 and Figures 6-2 and 6-4 in section 6.3.1, that all models except DRAINMOD-K_s-STMAX, between September 1995 and November 1996, over-predicted surface runoff.

As explained in section 6.3.1 above, a possible reason for under-prediction by the DRAINMOD-K_s-STMAX model between September 1995 and November 1996 could be due to leveling/grading operation and addition of lime and nitrogen on the research plots done mid to end February 1996, which could have reduced both soil surface depressional storage and vertical saturated hydraulic conductivity of the top layer.

The same information was used to determine by how much each modification improved the original DRAINMOD model's runoff prediction accuracy (Table 6-5 and Table 6-6).

Table 6-3. Comparison between measured, original and modified DRAINMOD models – September 1995 to November 1996. TMRO is total measured runoff, TPRO is total predicted runoff, and RO diff. is runoff difference

Model	TMRO (cm)	TPRO (cm)	%RO diff.
DRAINMOD-ORIGINAL	18.01	26.23	45.62
DRAINMOD-STMAX	18.01	21.54	19.58
DRAINMOD-K_s	18.01	20.26	12.49
DRAINMOD-K_s-STMAX	18.01	16.50	-8.38

Table 6-4. Comparison between measured, original and modified DRAINMOD models – November 1996 to November 1997

Model	TMRO (cm)	TPRO (cm)	%RO diff.
DRAINMOD-ORIGINAL	21.98	33.86	54.06
DRAINMOD-STMAX	21.98	30.61	39.26
DRAINMOD-K_s	21.98	28.49	29.59
DRAINMOD-K_s-STMAX	21.98	26.55	20.79

All modified models had better predictions than the original DRAINMOD model, which was shown by the smaller percent runoff difference (Tables 6-3 and 6-4). The original DRAINMOD (DRAINMOD-ORIGINAL) model over-predicted runoff by 45.62% between September 1995 and November 1996 and over-predicted runoff by 54.06% between November 1996 and November 1997. Both between September 1995 and November 1996 and between November 1996 and November 1997, the

DRAINMOD-K_s-STMAX model had the closest predictions to the measured runoff values, over-predicting by 21% between November 1996 and November 1997 and under-predicting by 8% between September 1995 and November 1996. The DRAINMOD-K_s model over-predicted runoff by 12.49% between September 1995 and November 1996 and over-predicted runoff by 29.59% between November 1996 and November 1997. Finally, the DRAINMOD-STMAX model over-predicted runoff by 19.58% between September 1995 and November 1996 and over-predicted runoff by 39.26% between November 1996 and November 1997.

Compared with the predictions by the original DRAINMOD model, all three modified DRAINMOD models improved runoff predictions between September 1995 and November 1996 (Table 6-5) and between November 1996 and November 1997 (Table 6-6) and shown by Figure 6-2 and Figure 6-4. Modified DRAINMOD models' surface runoff prediction improvements varied from a minimum of 27% by the DRAINMOD-STMAX model between November 1996 to November 1997 to a maximum of 82% by the DRAINMOD-K_s-STMAX model between September 1995 and November 1996. As expected, the DRAINMOD-K_s-STMAX model, which combined vertical saturated hydraulic conductivity and maximum surface depressional storage modifications, improved the original DRAINMOD the most both between September 1995 and November 1996 season (82%) and between November 1996 and November 1997 (62%).

Table 6-5. Runoff prediction improvement by the three modified DRAINMOD models – September 1995 to November 1996. Where Diff. of % RO diff. is the difference between original DRAINMOD prediction and the modified DRAINMOD modifications

Model	**Absolute %RO diff.**	**Diff. of %RO diff.**	**% pred. improvement**
DRAINMOD-ORIGINAL	45.62	0.00	0.00
DRAINMOD-STMAX	19.58	26.04	57.08
DRAINMOD-K_s	12.49	33.13	72.62
DRAINMOD-K_s-STMAX	8.38	37.24	81.63

Table 6-6. Runoff prediction improvement by the three modified DRAINMOD models – November 1996 to November 1997. Where Diff. of % RO diff. is the difference between original DRAINMOD prediction and the modified DRAINMOD modifications

Model	**Absolute %RO diff.**	**Diff. of %RO diff.**	**% pred. improvement**
DRAINMOD-ORIGINAL	54.06	0.00	0.00
DRAINMOD-STMAX	39.26	14.80	27.38
DRAINMOD-K_s	29.59	24.47	45.26
DRAINMOD-K_s-STMAX	20.79	33.27	61.54

6.4 Conclusions

Between September 1995 and November 1996, the predicted runoff by the original DRAINMOD model was significantly different from the measured runoff (p-value = 0.03) whereas the predicted runoff by the modified DRAINMOD-STMAX, DRAINOD-K_s and the combined DRAINMOD-K_s-STMAX models were not significantly different (p-value = 0.35, 0.47 and 0. 65 respectively). The total predicted runoff by the DRAINMOD-K_s-STMAX model (16.50 cm) was closest to the measured runoff (18.01 cm), followed by the total predicted runoff by the DRAINMOD-K_s (20.26 cm), and by the DRAINMOD-STMAX (21.54 cm) models respectively. Between November 1996 and November 1997, the predicted runoff by the original DRAINMOD model (p-value = 0.12), the modified DRAINMOD-STMAX (p-value = 0.26), DRAINMOD-K_s (p-value = 0.43) and the combined DRAINMOD-Ks-STMAX (p-value

= 0.57) models were not significantly different from the measured runoff. However, total runoff predicted by the modified DRAINMOD models was closer to the total measured runoff than the total runoff predicted by the original DRAINMOD model (33.86 cm), with total predicted runoff by the DRAINMOD-K_s-STMAX model (26.55 cm) being closest to the total measured runoff (21.98 cm), followed that by the DRAINMOD-K_s (28.49 cm) and the DRAINMOD-STMAX (30.61 cm) models respectively, the same order as in the previous season.

Regression analysis between the predicted and measured daily and cumulative runoff indicated that during the period September 1995 through November 1996, there was a good correlation (high R^2 values) between the predicted and measured runoff both for the daily and cumulative runoff, with DRAINMOD-K_s-STMAX model having the best correlation between its daily and cumulative predicted runoff values and the measured values ($R^2 = 0.98$ and $R^2 = 0.99$ respectively). However, between November 1996 and November 1997, there was not good correlation between predicted and measured runoff for the daily both for all the DRAINMOD models with the best being between the runoff predicted by the original model and the measured daily runoff (R^2 = 0.38) but there was a good correlation between the measured and predicted cumulative runoff for all DRAINMOD models with the least being $R^2 = 0.96$ by the original DRAINMOD model. There was no clear explanation for the poor correlation for the daily runoff data between November 1996 and November 1997 whereas the correlation between September 1995 and November 1996 being good. Differences in the rainfall patterns for different years in this region (Keim and Faiers, 1996; Bengtson and Carter, 2004) could explain the observed correlation differences. Therefore, further validation work is needed to determine the reliability of the modified DRAINMOD models under different weather conditions.

All models except DRAINMOD-K_s-STMAX, between September 1995 and November 1996, over-predicted surface runoff. A possible reason for under-prediction by the DRAINMOD-K_s-STMAX model between September 1995 and November 1996 could be due to leveling/grading operation and addition of lime and nitrogen on the research plots done in mid February 1996, which could have reduced both soil surface depressional storage and vertical saturated hydraulic conductivity of the top layer. The modified DRAINMOD models' surface runoff predictions were closer to the measured surface runoff than that of the original DRAINMOD model. DRAINMOD-K_s-STMAX model, which under-predicted runoff by 8% between September 1995 and November 1996 and over-predicted runoff by 21% between November 1996 and November 1997 had the closest runoff predictions to runoff measurements. The DRAINMOD-K_s, DRAINMOD-STMAX and the original DRAINMOD models over-predicted runoff by 13%, 20% and 46% respectively between September 1995 and November 1996 and by 30%, 39% and 54% between November 1996 and November 1997 respectively.

Using the original DRAINMOD model runoff prediction as the reference, DRAINMOD-STMAX, DRAINMOD-K_s and DRAINMOD-K_s-STMAX model improved surface runoff prediction by 57%, 73%, and 82% respectively between September 1995 and November 1996 and by 27%, 45%, and 62% respectively between November 1996 and November 1997.

Although DRAINMOD-K_s-STMAX model predicted cumulative runoff was closest to the measured cumulative runoff more modifications, such as the modification to include the rainfall intensity factor as explained in Chapter 3, are needed to improve the accuracy of predictions by DRAINMOD-K_s-STMAX model. However, the current DRAINMOD-K_s-STMAX model after further validation could be used to quantify the benefits of deep chiseling under various weather conditions, to determine how frequent to deep chisel and how close to planting time farmers should deep chisel to draw maximum deep chiseling benefits. The findings of such research would need to be relayed to engineers, scientists and farmers.

CHAPTER SEVEN

BENEFITS OF MODELING THE EFFECTS OF DEEP CHISELING A SOUTHERN ALLUVIAL SOIL WITHIN DRAINMOD ON THE ESTIMATION OF INFILTRATION AND SURFACE RUNOFF

7.1 Introduction

Alluvial soils, deposited by floodwaters over thousands of years, cover the Red River valley, Mississippi Alluvial Plain and other stream valleys along the Mississippi River. These soils, when fertilized, properly farmed and provided with sufficient rainfall during the growing season are very productive, with high crop yields. For example, agriculture contributed approximately $ 9 billion to Louisiana's economy in 2003 (LSU Agcenter, 2004). According to LSU Agcenter (2004), the total farm value of plant enterprises alone in 2003 was $2.614 billion and the value added was $3.413 billion for a total value of all crop enterprises to the Louisiana economy of $6.027 billion [67% of agricultural contribution to the economy]. Besides the types of alluvial soils and crop inputs such as fertilizers and pesticides, crop yields are very much dependent on the amount, duration, and distribution of rainfall during the crop-growing season.

The primary source of water for agricultural production, for many parts of the world is rainfall or precipitation. Precipitation is high in Louisiana, with annual precipitation often exceeding 1500 mm and monthly rainfall frequently exceeds 250 mm (Fouss, et al., 1987). Occasionally annual precipitation exceeds 2000 mm in this area (Bengtson and Carter, 2004). Too much water is undesirable because it can lead to a rise of the groundwater table and undesirable saturation of the root zone if there is no drainage. Precipitation is not always high but in some years, it may be low. Too little water during the growing season causes plants to wilt, resulting in loss of crop yield or even crop failure where there is no irrigation.

The distribution of rainfall in Louisiana varies from year to year, season-to-season, month to month, day-to-day, hour-to-hour and within the hour (LSU AgCenter Climate, 2004). According to Bengtson and Carter (2004), the average annual rainfall for the period 1988 to 2000 in Baton Rouge Louisiana was 1550 mm, with annual rainfall ranging from a high of 1997 mm in 1992 to a low of 998 mm in 2000. Due to high amounts of rainfall in the southeastern United States (Bengtson and Carter, 2004), the rainfall intensities are generally high even with long duration storms in the winter and spring seasons.

High intensity rainfall is less utilizable by the crops than low intensity rainfall because most of the rainwater runs off the ground surface and does not infiltrate into the root zone for crop use. In addition high intensity rainfall usually has high-energy raindrops that fall on the soil surface. In fine textured soils, like alluvial soils, the soil aggregates rapidly break down into fine particles that seal the soil surface especially during seedbed preparation when the soil is bare (Haan et al., 1994). The soil surface seal is compacted by further raindrops. Upon drying, the cementing agents in clays form and bind soil particles together forming a continuous sheet (crust) on the soil surface (Martinez-Gamino, 1994). Soil surface seal formation leads to lower soil water infiltration and increased soil surface runoff, both of which have a negative effect on crop yields and water pollution.

High runoff leads to lower crop yields because of the loss of crop nutrients such as nitrogen, phosphorus and potassium. Loss of crop nutrients (Bengtson et al., 1998;

Willis et al, 1998) and pesticides (Bengtson et al., 1989; Southwick et al., 2003) also leads to water pollution, which could pose a great danger to aquaculture and aquatic life. Using historical data Goolsby et al., (2000) showed that concentration of nitrate in the Mississippi River and some of its tributaries have increased by 2 to more than 5 times since the early 1900s with the principal source being basins that drain agricultural fields along the Mississippi River and its tributaries. Nitrogen from croplands can lead to oxygen-depleted water in the runoff destination waters, which may endanger the aquatic life. For example in the summer of 1999, billions of creatures suffocated in the northern Gulf of Mexico, starting in the spring [right after the application of fertilizers and herbicides] when waters were gradually depleted of life-giving oxygen (Ferber, 2001). Therefore, water runoff from pollution is a great concern to aquaculture, freshwater fish, and marine fish farmers who depend on it for livelihood.

The total farm value of all fish and wildlife enterprises in Louisiana was $446.5 million for 2003 and the value added was $327.4 million for a total value of all fishery and wildlife enterprises to Louisiana economy was $773.9 million (approximately 9% of the total agricultural contribution) (LSU Agcenter, 2004). Of the total farm value of all fish and wildlife enterprises, 88% was contributed by the combination of aquaculture, freshwater fisheries, and marine fisheries.

In addition to economic losses for farmers engaged in aquaculture caused by high levels of nutrient concentrations in surface runoff, pesticides may cause contamination to the fish (Dowd et al., 1985), which could pose serious health risks to humans. In addition, if the nitrates (> 10ppm nitrate-N) in the surface runoff end in drinking water streams and wells, it can lead to health problems in humans. In human blood NO_3- is reduced to NO_2-

reacts to reduce the capacity of red blood cells to carry oxygen, and causes a blood disorder known as methemoglobinaemia or blue baby syndrome (Bruninng-Fann and Kaneene, 1993). Therefore, it is desirable to adopt farming practices that will reduce surface runoff during wet years by increasing soil water infiltration in addition to using just sufficient amount of fertilizers for crop growth to avoid groundwater contamination due to leaching.

Tillage is the most commonly used management practice to break the surface soil seal and restore reasonably high infiltration rates to reduce runoff and improve crop yields (Rao, 2004). One of the tillage practices that have been in Louisiana to break the surface seal on alluvial soils and reduce runoff and improve yields is deep chiseling (Bengtson et al., 1995). Deep chiseling used to be a common practice in Lower Mississippi River Valley, but in recent years, farmers do not use it because they did not see any economic benefits and because minimum tillage has been widely adopted in the last ten years (Grigg and Fouss, 2002). According to the results by Grigg et al. (2003), deep chiseling [just before the growing season] may be necessary if subsurface drainage is to reduce nutrient loss in surface runoff from the Commerce silt loam soil.

To deep chisel a field a farmer attaches short angled subsoil shanks to a tractor tool bar and pulls them through the soil, breaking the soil to at least 30cm below the ground surface (Grigg and Fouss, 2002). Deep chiseling increases infiltration and reduces surface runoff by increasing the vertical component of saturated hydraulic conductivity (K) of the top layer of soil (Kincaid, 2002) and by increasing the maximum surface depressional storage (STMAX) (Kamphorst et al., 2000; Kincaid, 2002; Guzha, 2004). Roughly tilled fields hold considerable amounts of water in the surface depressions

(Idowu et al., 2002; Guzha, 2004) thus reducing surface runoff as opposed to smooth surface fields, which lead to high surface runoff. Some of the ponded water held in the surface depressional storage infiltrates into the subsoil and some evaporates into the atmosphere.

Unfortunately, the benefits of deep chiseling are only temporary because the soil surface seal reforms and soil compaction increases gradually to the previous condition as the fine particles fill the soil pore spaces and surface depressions are smoothed out after subsequent rainfall events (Rao et al, 1998b; Allen and Musick, 2001). Currently there is not sufficient information available to advise the farmers how often to deep chisel their farm fields to maximize the benefits associated with deep chiseling. Farmers and researchers decide on the frequency of deep chisel based on their farming experience, which may or may not be correct. Therefore, there is a need to model the benefits of deep chiseling depending on climatic conditions over time after deep chiseling to determine how often to deep chisel. This requires the use of accurate infiltration models to determine infiltration and runoff from a particular rainfall event at different stages of surface seal reformation to estimate the increased crop yields and reduced pollution benefits.

7.1.1 Study Goals

1. To use the DRAINMOD-K_s-STMAX model to quantify the benefits of deep chiseling for increasing infiltration and subsurface drainage and lowering surface runoff. This was accomplished by comparing the predictions obtained using the original DRAINMOD model, which assumes that deep chiseling does not have an effect on

infiltration, subsurface drainage or surface runoff, with the predictions obtained by using the DRAINMOD-K_s-STMAX model.

2. To use the DRAINMOD-K_s-STMAX model to determine how long it takes to lose the benefits of deep chiseling a Commerce silt loam, a southern alluvial soil.
3. To use the DRAINMOD-K_s-STMAX model to determine how close to planting season farmers need to deep chisel to take advantage of the benefits of deep chiseling a Commerce silt loam, a southern alluvial soil.

7.2 Materials and Methods

The original DRAINMOD model and DRAINMOD-K_s-STMAX model simulations were run using annual weather data collected from the USDA-ARS Ben Hur Research site, described in detail in section 4.2.1 of Chapter 4. The weather data considered was for the periods September 28, 1995 to November 21, 1996 and November 22, 1996 to November 22, 1997 when deep chiseling was carried out on the Commerce silt loam soil at Ben Hur Research location.

To quantify the benefits of deep chiseling, the predictions obtained by using the original DRAINMOD model, which assumes that deep chiseling does not have an effect on infiltration, subsurface drainage or surface runoff, were compared with the predictions obtained by using the DRAINMOD-K_s-STMAX model. The benefits of deep chiseling were considered over when vertical saturated hydraulic conductivity (K_s) had reduced to the value just before deep chiseling the plots or its final steady state value (K_{sf}) using Equation 5-2 and therefore, another deep chiseling operation was needed. The parameters in Equation 5-2 for the Commerce silt loam soil were 2cm/kr for "K_{si}", 0.5 cm/hr for "K_{sf}" and 0.03 cm^{-1} for "a". With all these parameters known, it was possible to calculate the infiltration capacity since deep chiseling a Commerce silt loam soil that corresponded to any particular K_{st} value.

The percentage by which K_s has reduced since deep chiseling a field was then calculated using the difference between the initial maximum K_s and the current K_s. The approximate date corresponding to 10% through 100% K_s decrease at 10% intervals was recorded to determine the fraction of deep chiseling benefits still remained by planting time. The planting date in 1996 was on March 29 and in 1997, it was in April 22.

7.3 Results and Discussion

7.3.1 Quantifying the Benefits of Deep Chiseling

Comparing the infiltration, subsurface drainage, and surface runoff outputs by the original DRAINMOD model and the DRAINMOD-K_s-STMAX model, it was determined that deep chiseling increased infiltration by 9.4% from 127.28 cm to 139.19 cm, increased subsurface drainage by 2.1 % from 72.81 cm to 74.34cm, and reduced runoff by 19.7% from 60.37 cm to 48.46 cm between September 1995 and November 1996 (Table 7-1).

Table 7-1. Benefits of deep chiseling – September 1995 to November 1996 (CI is cumulative infiltration, CRO is cumulative runoff, CSD is cumulative subsurface drainage, % IC, ROC, and SDC is % infiltration , runoff, and subsurface drainage difference respectively between DRAINMOD-K_s-STMAX and DRAINMOD-ORIGINAL predictions) based on DRAINMOD-ORIGINAL

Model	**CI (cm)**	**CRO (cm)**	**CSD (cm)**	**% IC**	**% ROC**	**%SDC**
DRAINMOD-ORIGINAL	127.28	60.37	72.81	9.40	-19.70	2.10
DRAINMOD-K_s-STMAX	139.19	48.46	74.34			

Between November 1996 and November 1997 deep chiseling operation increased infiltration by 5.7% from 141.98 cm to 150.07 cm, increased subsurface drainage by 10.8% from 74.90 cm to 82.96 cm, and reduced runoff by 19.20% from 42.80 cm to 34.19 cm (Table 7-2).

Table 7-2. Benefits of deep chiseling – November 1996 to November 1996 (CI is cumulative infiltration, CRO is cumulative runoff, CSD is cumulative subsurface drainage, % IC, ROC and SDC is % infiltration, runoff and subsurface drainage difference respectively between DRAINMOD-K_s-STMAX and DRAINMOD-ORIGINAL predictions) based on DRAINMOD-ORIGINAL

Model	**CI (cm)**	**CRO (cm)**	**CSD (cm)**	**% IC**	**% ROC**	**%SDC**
DRAINMOD-ORIGINAL	141.98	42.80	74.90	5.70	-19.20	10.80
DRAINMOD-K_s-STMAX	150.07	34.19	82.96			

7.3.2 Frequency and Timing of Deep Chiseling for Alluvial Soils

All benefits of deep chiseling are lost whenever the current vertical saturated hydraulic conductivity reaches the final steady state value, in this case 0.5 cm/hr. The amount of cumulative rainfall corresponding to this value, calculated using Equation 5-2, was about 115 cm. This implies that farmers in Louisiana would need to deep chisel their fields once every year because average annual rainfall is about 150 cm. Between September 1995 and November 1996 deep chiseling benefits were not evident in the measured data approximately nine months after deep chiseling (Table 7-3). Between November 1996 and November 1997, there were no deep chiseling benefits after seven months (Table 7-4). This shows that the length of time of benefiting from deep chiseling a field depends on the prevailing weather conditions.

Table 7-3. Determination of frequency and timing of deep chiseling for Commerce silt loam – September 1995 to November 1996

Date	Cum. Rainfall (cm)	K_s (cm/hr)	% K_s decrease
09/28/95	0.00	2.0	0
10/14/95	12.10	1.5	11
11/02/95	28.88	1.1	25
12/06/95	36.31	1.0	32
12/08/95	51.98	0.8	45
01/24/96	58.06	0.8	50
02/28/96	71.58	0.7	62
03/29/96*	**75.13**	**0.7**	**65**
04/13/96	80.29	0.6	70
04/24/96	92.71	0.6	81
05/30/96	104.55	0.6	91
06/25/96	114.82	0.5	100

Table 7-4. Determination of frequency and timing of deep chiseling for Commerce silt loam – November 1996 to November 1997

Date	Cum. Rainfall (cm)	K_s (cm/hr)	% K_s decrease
11/22/96	0	2.0	0
12/18/96	10.24	1.6	9
01/22/97	23.07	1.3	20
02/12/97	37.00	1.0	32
02/25/97	47.26	0.9	41
04/04/97	55.97	0.8	49
04/22/97	**63.90**	**0.7**	**56**
04/26/97	69.54	0.7	60
05/15/97	80.96	0.6	70
05/24/97	92.41	0.6	80
06/16/97	102.77	0.6	89
06/17/97	114.96	0.5	100

The data indicated in bold illustrate the deep chiseling benefits at the time of planting. During the period beginning September 1995 to November 1996, 65% of the benefits of deep chiseling deep benefits were lost. During the period beginning November 1996 to November 1997, 56% of the benefits of deep chiseling benefits had been lost. This was partly due the amount of rainfall between the time of deep chiseling and planting date and partly because of how close to the planting date deep chiseling was done. Generally, the further from the planting time deep chiseling operation is done, the greater the loss of the deep chiseling operation. Therefore, it is very important for farmers to deep chisel their fields close to the planting time in order to get maximum benefits from deep chiseling.

7.4 Conclusions

Deep chiseling a Commerce silt loam soil increased infiltration by 9.4% and subsurface drainage by 2.1% and reduced runoff by 19.7% between September 28, 1995 and November 21, 1996 and by 5.7%, 10.8%, and 19.2% respectively between November 22, 1996 and November 22, 1997. All benefits resulting from deep chiseling are lost after 115 cm of rainfall since deep chiseling a field. For wet states like Louisiana with annual rainfall often exceeding 150 cm (Fouss et al., 1987) this translates into deep chiseling once every year whereas in dry states deep chiseling can be done once every two to three years depending on the amount of rainfall.

Depending on the amount of rainfall after deep chiseling and how long after deep chiseling before the planting season, farmers can lose 60% or more of the maximum deep chiseling benefits. Because of great rainfall variability in Louisiana and other southern states (Keim and Faiers, 1996; Bengtson and Carter, 2004), it is advisable for farmers to deep chisel their fields just before the planting season.

Finally cost-benefit analysis could be done to determine the benefits of deep chiseling in monetary terms to encourage crop farmers adopt deep chiseling recommendations, especially if these recommendations given increase crop yields while creating a clean environment. These benefits result from increased crop yield returns due

---

* Bold indicates the date corn planting was done

to increased water infiltration and reduced runoff less the cost of deep chiseling operations, reduced crop input costs because of reduced surface runoff, and finally profits resulting from increased aquaculture and marine and freshwater fish production.

CHAPTER EIGHT

GENERAL SUMMARY, CONCLUSION, AND RECOMMENDATION

Exposure of fine textured alluvial soils, deposited by floodwaters over thousands of years in Louisiana, to high amounts of rainfall in this region leads to the formation of a soil surface seal, which upon drying form a continuous sheet (crust) on the soil surface (Martinez-Gamino, 1994). Soil surface seal formation coupled with machine traffic during field operations reduces water infiltration and increases surface runoff (Hillel, 1982). Low water infiltration and high runoff may result in less water and crop nutrients available within the crop root zone leading to lower crop yields and increased water pollution into the surrounding water streams, which may pose a serious danger to aquatic life in the surface runoff destination waters. Therefore, aquatic and crop farmers and environmentalists need information and advice on cost-effective best management practices (BMPs) that will increase crop yields by increasing the flow of water and crop nutrients into the crop root zone while reducing water pollution.

The design of optimum agricultural water management systems requires data for different possible designs depending on the climatic conditions for a given soil type and field situation. One tool that has been used by engineers and researchers to generate the needed data is modeling. The success of any model to aid engineers and researchers in their efforts to design optimum agricultural water management systems depends to a large extent on its ability to accurately estimate the components or elements being evaluated. One model that has been developed (Skaggs, 1978), modified (Bengtson et al., 1985; Fouss, 1985; Fouss et al., 1989), and used (Gayle and Skaggs, 1978; Fouss et al., 1987; Wright et al., 1992; Saleh et al., 1994) for the alluvial soils of Louisiana is

DRAINMOD. DRAINMOD is a computer model that was developed at North Carolina State University in the late 1970s (Skaggs, 1978). This model predicts surface runoff, water table depth, drainage outflow, soil water content, evapotranspiration (ET) and infiltration on hourly, daily, monthly or an annual basis in response to given soil properties, crop variables, climatological data, and site parameter inputs.

However, DRAINMOD does not accurately predict infiltration and runoff for the crusting prone alluvial soils of Louisiana. The following are some of the possible reasons for this inaccurate prediction by DRAINMOD: (1) The use of hourly rainfall time increments (2) Assumption of constant Green-Ampt parameters and hence constant vertical saturated hydraulic (K_s) and (3) Assumption that maximum surface depressional storage (STMAX) is constant irrespective of tillage operations.

Hourly rainfall rates may result in inaccurate prediction of infiltration and runoff in the southeastern United States where rainfall amounts are significant (Bengtson and Carter, 2004) and where all rainfall in a given event may fall within minutes (LSU AgCenter Climate, 2004). On the other hand soil surface seal formation on alluvial soils such as the Commerce silt loam soil [fine silty, mixed, non-acid, thermic Aeric Flivaquent], a southern Louisiana alluvial soil may lead to inaccurate prediction of infiltration rates and hence infiltration and runoff by DRAINMOD.). A tillage practice that has been used in Louisiana to break the soil surface crust and the hardpan in the deeper layers in order to increase infiltration and reduce surface runoff is deep chiseling (Bengtson et al, 1995).

Deep chiseling increases infiltration and reduces surface runoff by increasing the vertical component of saturated hydraulic conductivity (K_s) of the top layer of soil and increasing the maximum surface depressional storage (STMAX). Unfortunately, the benefits of deep chiseling are only temporary because the soil surface seal reforms and soil compaction increases gradually to the previous condition as the fine particles fill the soil pore spaces and surface depressions are smoothed out after subsequent rainfall events. The above conditions will decrease K_s and STMAX.

Although K_s and STMAX decrease gradually depending on total rainfall (Freebairn et al., 1991) over time [cumulative rainfall since deep chiseling], the current DRAINMOD model assumes both K_s and STMAX remain constant irrespective of any tillage practice carried out (Skaggs, 1978). Therefore, the current DRAINMOD model is likely to give less accurate predictions of both infiltration and runoff depending on the stage of surface seal reformation, which is a function of cumulative rainfall since the deep chiseling operation. As a result, the current DRAINMOD model cannot be used to quantify how long farmers and environmentalists may benefit from a particular deep chiseling operation and how frequently to deep chisel a farm field, both of which depend on the climatic factors such as cumulative rainfall since deep chiseling.

To model the variation of vertical saturated hydraulic conductivity (K_s) at different stages of surface seal reformation on alluvial soils of Louisiana after deep chiseling explained in section 2.8 of Chapter two) into DRAINMOD model, field experiments were conducted to calibrate the dynamic K_s model.

The field study on the variation of vertical saturated hydraulic conductivity depending on cumulative rainfall after deep chiseling the Commerce silt loam soil had mixed results. Vertical saturated hydraulic conductivity decreased exponentially with increasing cumulative rainfall ($R^2 = 0.79$) for measurements taken when the soil volumetric moisture content was less than 38% (selected depending on the distribution of the field data), which was determined based on the field data for the Commerce silt loam. On the contrary vertical saturated hydraulic conductivity increased exponentially with increasing cumulative rainfall for measurements taken when the soil volumetric moisture content was equal or greater than 38% ($R^2 = 0.65$). Vertical saturated hydraulic conductivity (K) measurements taken when the soil volumetric moisture content (VMC) was less than 38% were significantly lower than K measurements taken when VMC was equal or greater than 38% (p-value = 0.002). A possible reason for the lower vertical saturated hydraulic conductivity could be entrapped air (Bouwer, 1966), which prevents water movement in air-filled pores consequently reducing the hydraulic conductivity measured in the field by as much as 50 percent compared to conditions when trapped air is not present (Reynolds and Elrick, 1986). Although there was no clear-cut relationship between vertical saturated hydraulic conductivity and cumulative rainfall after deep chiseling, information gained from this research was used to calibrate a dynamic vertical saturated hydraulic conductivity model.

Based on the theory of soil surface seal formation and past work a mathematical model, in which vertical saturated hydraulic conductivity decreases exponentially with cumulative rainfall after deep chiseling from a maximum value to a steady state (final) value as expressed, was developed. Using data measured after deep chiseling a Commerce silt loam, a southern alluvial soil, the equation parameters were determined. Initial vertical saturated hydraulic conductivity (K_{si}) was 2.0 cm/hr, final vertical saturated hydraulic conductivity (K_{sf}) was 0.50 cm/hr, and the exponent a, which depends on soil type, was 0.03 cm^{-1}. The model was then coded using Microsoft FORTRAN

PowerStation version 4.0 (Microsoft Corporation, 1995) and incorporated into DRAINMOD. In addition, a mathematical maximum surface depressional storage (STMAX) model was developed (Gayle and Skaggs, 1978; Onstad, 1984; Kincaid, 2002). STMAX was hypothesized to decrease exponentially, depending on the number of days after deep chiseling, from a maximum value to a steady state (final) value. Using data by Gayle and Skaggs (1978) that was adjusted for deep chiseling operation (RUSLE, 1997), equation parameters were determined. Initial maximum surface depressional storage (MAXSTI) was 1.25 cm, final maximum surface depressional storage (MAXSTF) was 0.10 cm, and the exponent Amaxs was 0.012 day^{-1}. This model was then coded using Microsoft FORTRAN PowerStation version 4.0 (Microsoft Corporation, 1995) and incorporated into DRAINMOD.

The sensitivity of the computed total runoff, total infiltration and total drainage to changes in K_{si} and MAXSTI shows that changes in these parameters do not cause large changes in the computed DRAINMOD components above. However, an increase in K_{si} causes a significant decrease in daily runoff on some days while the same increase does not cause a significant decrease in daily runoff. This observation could be due to the differences in rainfall intensities, with the greatest effect of K_{si} on daily runoff during high intensity rain events and least effect when the rainfall intensity is low. Changes in MAXSTI slightly changed the calculated daily runoff. Although, the changes in the daily runoff due to changes in K_{si} and MAXSTI are small, it is still important to determine accurately these parameters to ensure accurate model estimation.

Validation of the original and modified DRAINMOD models show that between September 1995 and November 1996, the predicted runoff by the original DRAINMOD model was significantly different from the measured runoff (p-value = 0.03) whereas the predicted runoff by the modified DRAINMOD-STMAX, DRAINOD-K_s and the combined DRAINMOD-K_s-STMAX models were not significantly different (p-value = 0.35, 0.47 and 0. 65 respectively). The total predicted runoff by the DRAINMOD-K_s-STMAX model (16.50 cm) was closest to the measured runoff (18.01 cm), followed by the total predicted runoff by the DRAINMOD-K_s (20.26 cm), and by the DRAINMOD-STMAX (21.54 cm) models respectively. Between November 1996 and November 1997, the predicted runoff by the original DRAINMOD model (p-value = 0.12), the modified DRAINMOD-STMAX (p-value = 0.26), DRAINMOD-K_s (p-value = 0.43) and the combined DRAINMOD-Ks-STMAX (p-value = 0.57) models were not significantly different from the measured runoff. However, total runoff predicted by the modified DRAINMOD models was closer to the total measured runoff than the total runoff predicted by the original DRAINMOD model (33.86 cm), with total predicted runoff by the DRAINMOD-K_s-STMAX model (26.55 cm) being closest to the total measured runoff (21.98 cm), followed that by the DRAINMOD-K_s (28.49 cm) and the DRAINMOD-STMAX (30.61 cm) models respectively, the same order as in the previous season.

Regression analysis between the predicted and measured daily and cumulative runoff indicated that during the period September 1995 through November 1996, there was a good correlation (high R^2 values) between the predicted and measured runoff both for the daily and cumulative runoff, with DRAINMOD-K_s-STMAX model having the best correlation between its daily and cumulative predicted runoff values and the measured values ($R^2 = 0.98$ and $R^2 = 0.99$ respectively). However, between November

1996 and November 1997, there was not good correlation between predicted and measured runoff for the daily both for all the DRAINMOD models with the best being between the runoff predicted by the original model and the measured daily runoff (R^2 = 0.38) but there was a good correlation between the measured and predicted cumulative runoff for all DRAINMOD models with the least being R^2 = 0.96 by the original DRAINMOD model. There was no clear explanation for the poor correlation for the daily runoff data between November 1996 and November 1997 whereas the correlation between September 1995 and November 1996 being good. Differences in the rainfall patterns for different years in this region (Keim and Faiers, 1996; Bengtson and Carter, 2004) could explain the observed correlation differences. Therefore, further validation work is needed to determine the reliability of the modified DRAINMOD models under different weather conditions.

All models except DRAINMOD-K_s-STMAX, between September 1995 and November 1996, over-predicted surface runoff. A possible reason for under-prediction by the DRAINMOD-K_s-STMAX model between September 1995 and November 1996 could be due to leveling/grading operation and addition of lime and nitrogen on the research plots done in mid February 1996, which could have reduced both soil surface depressional storage and vertical saturated hydraulic conductivity of the top layer. The modified DRAINMOD models' surface runoff predictions were closer to the measured surface runoff than that of the original DRAINMOD model. DRAINMOD-K_s-STMAX model, which under-predicted runoff by 8% between September 1995 and November 1996 and over-predicted runoff by 21% between November 1996 and November 1997 had the closest runoff predictions to runoff measurements. The DRAINMOD-K_s, DRAINMOD-STMAX and the original DRAINMOD models over-predicted runoff by 13%, 20% and 46% respectively between September 1995 and November 1996 and by 30%, 39% and 54% between November 1996 and November 1997 respectively.

Using the original DRAINMOD model runoff prediction as the reference, DRAINMOD-STMAX, DRAINMOD-K_s and DRAINMOD-K_s-STMAX model improved surface runoff prediction by 57%, 73%, and 82% respectively between September 1995 and November 1996 and by 27%, 45%, and 62% respectively between November 1996 and November 1997.

The DRAINMOD-K_s-STMAX model, which gave prediction values closest to the measured runoff values, was used to quantify the benefits of deep chiseling, to determine how frequent to deep chisel and how close to planting time farmers should deep chisel to draw maximum deep chiseling benefits. Deep chiseling a Commerce silt loam soil increased infiltration by 9.4% and subsurface drainage by 2.1%, and reduced runoff by 19.7% between September 28, 1995 and November 21, 1996 and by 5.7%, 10.8%, and 19.2% respectively between November 22, 1996 and November 22, 1997.

All benefits resulting from deep chiseling are lost after 115 cm of rainfall since deep chiseling a field. For wet states like Louisiana with annual rainfall often exceeding 150 cm (Fouss et al., 1987) this translates into deep chiseling once every year whereas in dry states deep chiseling can be done once every two to three years depending on the amount of rainfall. Depending on the amount of rainfall after deep chiseling and how long after deep chiseling before the planting season, farmers can lose 60% or more of the maximum deep chiseling benefits. Because of great rainfall variability in Louisiana and other southern states (Keim and Faiers, 1996; Bengtson and Carter, 2004), it is advisable for farmers to deep chisel their fields just before the planting season.

Although the modifications show promise, more work is needed to ensure repeatability of the model modification improvements. Below some are recommendations to achieve this goal.

1. Further work could be needed to determine if the variability of vertical saturated hydraulic conductivity (K) with respect to cumulative rainfall (R_c) after deep chiseling can be replicated. Other possible factors that could affect vertical saturated hydraulic conductivity would need to be investigated to determine why K exponentially increases with increasing R_c. One possible investigation factor could be to have a model that would correlate entrapped air with soil volumetric moisture content and hence water table depth to determine the current correction factor instead of using an assumed fixed factor (Skaggs, 1980) and thereby take into account the effect of entrapped air.

2. Although the runoff predictions by the DRAINMOD-STMAX, DRAINMOD-K_s and DRAINMOD-K_s-STMAX models show improvement, more validation is needed especially for different soils.

3. Although DRAINMOD-K_s-STMAX model prediction of cumulative runoff was closest to the measured cumulative runoff, modification to include the rainfall intensity factor (as explained in Chapter 3) are needed to further increase the accuracy of predictions. This could include using the algorithm described in the methodology in Chapter 3 to write a five-minute rainfall time increment (RI) subroutine and incorporating it into the current DRAINMOD model. The RI modified DRAINMOD model

(DRAINMOD-RI model) could then be validated using the surface runoff data from the USDA-ARS Ben Hur Research site measured between 1995 and 2001.

4. Finally, cost-benefit analysis could be done to determine the benefits of deep chiseling in monetary terms. In other words the costs of deep chiseling compared to increased yields resulting from increased infiltration and reduced runoff, reduced crop input costs because of using less but just sufficient crop inputs because of reduced surface runoff that usually washes them into water streams, and finally profits resulting from increased aquaculture and marine and freshwater fish production.

REFERENCES

Allen, R.R and J.T. Musick. 2001. Deep ripping and blocked furrow effects on lower 1/3 furrow irrigation infiltration. Applied Engineering in Agriculture 17(1):41-48.

Alyamani, M.S. and Z. Sen. 1993. Determination of hydraulic conductivity from complete grain-size distribution curves. Ground Water 31(4):551-555.

Amoozegar, A. and A.W. Warrick. 1986. Hydraulic conductivity of saturated soils - field methods. Methods of Soil Analysis. Part 1 Physical and Mineralogical Methods. Soil Science Society of America Book Series: 5: 834-838.

Ankey, M.D., T.C. Kaspar and M.A. Prieksat. 1995. Traffic effects on water infiltration in chisel-plow and no-till systems. Soil Sci. Soc. Am. J. 59:200-204.

Anonymous. 2002. Lower Mississippi Valley Ecosystem Restoration Initiative. URL: http://www.epa.gov/region4/programs/cbep/lowmiss.html. Last updated on Friday, May 24th, 2002.

Arya, L.M, F.J. Leij, P.J. Shouse and M.T. van Genuchten. 1999. Relationship between the hydraulic conductivity function and the particle-size distribution. Soil Sci. Soc. Am. J. 63:1063-1070.

Aslan, A. and W.J. Autin. 1998. Holcene flood-plain soil formation in the southern lower Mississippi Valley: implications for interpreting alluvial paleosols. Bulletin of the Geological Society of America 110(4):433-449.

Assouline, S. and Y. Mualem. 2002. Infiltration during soil sealing: the effect of areal heterogeneity of soil hydraulic properties. Water Resources Research 38(12):1286-1294.

ASTM Standards. 1998. Standard guide for comparison of field methods for determining hydraulic conductivity in the vadose zone. Designation: D 5126 – 90 (Reapproved 1998)$^{\varepsilon 1}$ ASTM, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA, USA.

Barisas, S.G, J.L.Baker, H.P. Johnson, and J.M. Laflen. 1978. Effect of tillage systems on runoff losses of nutrients, a rainfall simulation study. Transactions of the ASAE. 21:893-897.

Bear, J. 1972. Hydraulic radius models. Dynamics of Fluids in Porous Media. pp165-167. American Elsevier Pub. Co., New York.

Beasley, D.B., L.F. Huggins, and E.J. Monke. 1981. ANSWERS: A model for watershed planning. Transactions of the ASAE 23(4):938-944.

Bengtson, R.L., J.L. Fouss, and G.J. McCabe. 1985. Effects of evapotranspiration on modeling in southern Louisiana. Paper, American Society of Agricultural Engineers, No. 85-2516, pp15.

Bengtson, R.L, L.M. Southwick, G.H. Willis, and C.E. Carter. 1989. The influence of water tables on herbicide losses. National Water Conference. pp. 516-523.

Bengtson, R.L., C.E. Carter, J.L. Fouss, L.M. Southwick, and G. H. Willis. 1995. Agricultural drainage and water quality in Mississippi Delta. J. Irrigation and Drainage Eng. 121(4):292-295.

Bengtson, R.L, H.M. Selim and R. Ricaud. 1998. Water quality from sugarcane production on alluvial soils. Transactions of the ASAE 41(5): 1331-1336.

Bengtson, R.L. and C.E. Carter. 2004. The effect of subsurface drainage on water quality from soybeans. Drainage VIII. Technical Library. American Society of Agricultural Engineers. 21-24 March 2004. Sacramento California.

Boadu, F. K. 2000. Hydraulic conductivity of soils from grain-size distribution: new models. Journal of Geotechnical and Geoenvironmental Engineering 126:739-746.

Bouwer, H. 1961. A double tube method for measuring hydraulic conductivity of soil in sites above a water table. Soil Sci. Soc. Am. Proc. 25:334-342.

Bouwer, H. 1962. Field determination of hydraulic conductivity above a water table with a double-tube method. Soil Sci. Soc. Am. Proc. 26:330-335.

Bouwer, H. 1964. Measuring horizontal and vertical hydraulic conductivity of soil with the double-tube method. Soil Sci. Soc. Am. Proc. 28:19-23.

Bouwer, H. 1966. Rapid field measurement of air-entry value and hydraulic conductivity of soil as significant parameters in flow system analysis. Water Resource Research 2:729-738.

Bouwer, H. 1986. Intake rate: Cylinder infiltrometer. Methods of Soil Analysis. Part 1: Physical and Mineralogical Methods. Soil Science Society of America Book Series: 5: 834-838.

Bruning-Fann, C.S. and J.B. Kaneene. 1993. The effects of nitrate, nitrite and N-nitroso compounds on human health – A review. Vet. Hum. Toxicol. 35(6): 521-538.

Cassel, D. K., C.W. Raczkowski, and H.P. Denton. 1995. Tillage effects on corn production and soil physical conditions. Soil Sci. Soc. Am. J.59: 1436-1443.

Chartres, C.J., J.M. Kirby, and M. Raupach. 1990. Poorly ordered silica and aluminosilicates as temporary cementing agents in hard-setting soils. Soil Sci. Soc. Am. J. 54:1060-1067.

Cox, J.W., D.J. McFarlane, and R.W. Skaggs. 1994. Field evaluation of DRAINMOD for predicting waterlogging intensity and drain performance in South-Western Australia. Australian Journal of Soil Research. 32:653-671.

D'Andrea, R. 2001. Hydraulic conductivity of soils from grain-size; New models – Discussion. Journal of Geotechnical and Geoenvironmental Engineering. 127(10):899

Dillaha, T.A., M.L. Wolfe, A. Shirmohammadi, and F.W. Byne. 1998. ANSWERS-2000. ASAE Annual International Meeting, Orlando, Florida, USA, 12-16 July 1998, pp. 16.

Dowd, P.F., G.U. Mayfield, D.P. Coulon, J.B. Graves, and J.D. Newsom. 1985. Organochlorine residues in animals from three Louisiana watersheds in 1978 and 1979. Bulletin of Environmental Contamination and Toxicology 34(6): 832-841.

Duttweiler, D.W. and H.P. Nicholson. 1983. Environmental problems and issues of agricultural non-point source pollution. Agricultural Management and Water Quality. Pp 13-16. Editors, F.W. Schaller and G.W. Bailey. Ames, Iowa: Iowa State University Press.

Ferber, D. 2001. Keeping the stygian at bay. Science (Washington) 291(5506): 968-973.

Fouss, J.L. 1985. Simulated feedback-operation of controlled-drainage/subirrigation systems. Transactions of the ASAE 28(3): 839-847.

Fouss, J.L., R. L. Bengston and C. E. Carter. 1987. Simulating surface drainage in the Lower Mississippi Valley with DRAINMOD. Transactions of the ASAE 30(6): 1679-1688.

Fouss, J.L., J.S. Rogers and Cade E. Carter. 1989. Sump-controlled water table management predicted with DRAINMOD. Transactions of the ASAE 32(4): 1301-1308.

Fouss, J.L. and G.H Willis. 1990. Research need on integrated system for water and pest management to protect ground water quality. Irrigation and Drainage Proceedings of the 1990 National Conference IR Div/ASCE/Durango, CO/July 11-13.

Freebairn, D.M., S.C Gupta, and W.J Rawls. 1991. Influence of aggregate size and microrelief on development of surface soil crusts. Soil Sci. Soc. Am. J. 59:1436-1443.

Gayle, G.A. and R.W. Skaggs. 1978. Surface storage on bedded cultivated lands. Transactions of the ASAE 21(1):102-104, 109.

Gayle, G. A., R.W. Skaggs, and C.E. Carter. 1985. Evaluation of a water management model for a Louisiana sugarcane field. Journal American Society of Sugarcane Technology. 2:18-28.

Gicheru, P., C. Gachene, J. Mbuvi, and E. Mare. 2004. Effects of soil management practices and tillage systems on surface soil water conservation and crust formation on a sandy loam in semi-arid Kenya. Soil & Tillage Research 75(2): 173-184.

Goolsby, D.A., W.A. Battaglin, B.T. Aulenbach, and R.P. Hooper. 2000. Nitrogen flux and sources in the Mississippi River Basin. Science of the Total Environment 248(2/3): 75-86.

Grigg, B.C. and J.L. Fouss. 2002. Draining the land without polluting the waters. Agricultural Research/October 2002. pp4-8.

Grigg, B.C., L.M. Southwick, J.L. Fouss, and T.S. Kornecki. 2003. Drainage system impacts on surface runoff, nitrogen loss, and crop yield on a southern alluvial soil. Transactions of the ASAE. 46(6):1531-1537.

Guzha, A.C. 2004. Effects of tillage on soil microrelief, surface depression storage and soil water storage. Soil & Tillage Research 76(2):105-114.

Haan, C.T., B.J. Barfield, and J.C. Hayes. 1994. Infiltration. Design Hydrology and Sedimentology for Small Catchments, Academic Press, New York, USA. pp54-67.

Harleman, D.R.F., P.F. Melhorn and R.R. Rummer. 1963. Dispersion-permeability correlation in porous media. Journal of Hydraulic Division, American Society of Civil Engineers 89:67-85.

Hazen, A. 1892. Some physical properties of sand and gravels with special reference to their use in filtration. Massachusetts State Board of Health, 24th Annual Report pp 541-556.

Heatherly, L.G., C.D. Elmore, and R.A. Wesley. 1990. Corn, sorghum, and soybean response to irrigation in the Mississippi River alluvial plain. Crop Science 30(3): 665-672.

Hillel, Daniel. 1982. Infiltration and surface runoff. Introduction to Soil Physics. pp211.

Hillel, Daniel. 1980. Modern approaches to infiltration theory. Applications of Soil Physics. Academic Press. pp.16-24.

Hinkelmann, K. and O. Kempthorne. 1994. The generalized randomized block design. Design and Analysis of Experiments. Volume I Introduction to Experimental Design. Published by John Wiley & Sons, Inc. New York, Chichester, Brisbane, Toronto, Singapore. pp.279-290.

Huang, C.H. and J.M. Bradford. 1990. Depressional storage for Markov-Gaussian surfaces. Water Resources Research 26(9):2235-2242.

Idowu, O.J., R.J. Rickson and R.J. Godwin. 2002. Erosion as affected by tillage-induced roughness and surface mulch in a soil with a simulated subsurface pan. Transactions of the ASAE. 45(1):83-87.

Im, S.J., S.W. Park, Y.M. Chin, and K.S. Yoon. 2000. Development of CREAMS-PADDY model. 2000 ASAE Annual International Meeting, Milwaukee, Wisconsin, USA, 9-12 July 2000, pp. 1-13.

Kamphorst, E.C., V. Jetten, J. Guerif, J. Pitkanen, B.V. Iversen, J.T. Douglas, and A. Paz. 2000. Soil Sci. Soc. Am. J. 64(5):1749-1758.

Keim, B.D. and G.E. Faiers. 1996. Heavy rainfall distributions by seasons in Louisiana: synoptic interpretations and quantile estimates. Water Resources Bulletin 32(1):117-124.

Kim, S.J. and H.W. Chung. 1994. Field evaluation of layered Green-Ampt infiltration model considering temporal variation of physical properties. Transactions of the ASAE. 37(6):1845-1852.

Kincaid, D.C. 2002. The WEPP model for runoff and erosion prediction under sprinkler irrigation. Transactions of the ASAE. 45(1):76-72.

Koltermann, C.E. and S.M. Gorelick. 1995. Fractional packing model for hydraulic conductivity derived from sediment mixtures. Water Resources Research 31:3283-3297.

Kornecki, T.S. and J.L. Fouss. 2001. Quantifying soil trafficabilitity improvements provided by subsurface drainage for field crop operations in Louisiana. Applied Engineering in Agriculture 17(6):777-781.

Krumbein, W.C. and G.D. Monk. 1942. Permeability as a function of the size parameters of unconsolidated sand. American Institute of Mining Engineers, Technical Publication, pp153-163 (Littleton, Co, Am. Inst. Mining Eng.).

Levy, G.J., J. Levin, M. Gal, M. Ben-Hur, and I. Shainberg. 1992. Polymers' effects on infiltration and soil erosion during consecutive simulated sprinkler irrigations. Soil Sci. Soc. Am. J. 56:902-907.

Lindbo, D.L., F.E. Rhoton, W.H. Hudnall, N.E. Smeck, J.M. Bigham, and D.D. Tyler. 2000. Fragipan degradation and nodule formation in Glossic Fragiudalfs of the Lower Mississippi River Valley. Soil Sci. Soc. Am. J. 64: 1713-1722.

LSU AgCenter. 2004. Louisiana Summary: Agricultural and Natural Resource. http://www.agctr.lsu.edu/agsummary/ May 3rd, 2004.

LSU AgCenter Climate. 2004. The Louisiana Agriclimatic Information System. http://www.agctr.lsu.edu/weather/system.asp May 3rd, 2004.

Martinez-Gamino, M.A.1994. Crust formation in soils of Mexico and Louisiana. A Dissertation-Louisiana State University, Baton Rouge, Louisiana. pp.10.

Masch, F.D. and K.T. Denny. 1966. Grain-size distribution and its effects on the permeability of unconsolidated sand. Water Resources Research 2: 665-677.

McCarthy, E.J. and R.W. Skaggs. 1989. Comparison of two drainage simulation models using field data. Transactions of the ASAE 32:1933-1938.

McCuen, R. H. 1973. The role of sensitivity analysis in hydrologic modeling. Journal of Hydrology 18:37-53.

McMahon, P.C., S. Mostaghimi, and F.S. Wright. 1988. Simulation of corn yield by a water management model for a coastal plain soil. Transactions of the ASAE 31:734-742.

Microsoft Corporation. 1995. Microsoft FORTRAN PowerStation, professional edition. Document No. DD64081-0995. Printed in the United States of America.

Moore, I.D. and C.L. Larson. 1979. Estimating micro-relief surface storage from point data. Transactions of the ASAE 22(5):1073-1077.

Moore, S.H. 1998. Optimum soil-applied nitrogen levels for cotton on a high PH alluvial soil. Journal of Plant Nutrition (USA) 21(6):1139-1144.

Morari, F. and W.G. Knisel. 1997. Modifications of the GLEAMS model for crack flow. Transactions of the ASAE 40(5):1337-1348.

Onstad, C.A. 1984. Depressional storage on tilled soil surfaces. Transactions of the ASAE 27(3):729-732.

Pearce, A.D., C.R. Dillon, T.C. Keisling, C.G. Friddle, and M.P. Popp. 1999. Using deep tillage to improve yields from dryland soybeans: An economic analysis. Proceedings of the 22nd Annual Southern Conservation Tillage Conference for Sustainable Agriculture. Tifton, GA. 6-8 July 1999. Georgia Agriculture Experiment Station Special Publication 95. Athens, GA.

Rao, K.P.C., T.S. Steenhuis, A.L. Cogle, S.T. Srinivasan, D.F. Yule, and G.D. Smith. 1998a. Rainfall infiltration and runoff from an Alfisol in semi-arid tropical India. No-till systems. Soil & Tillage Research 48(1): 51-59.

Rao, K.P.C., T.S. Steenhuis, A.L. Cogle, S.T. Srinivasan, D.F. Yule, and G.D. Smith. 1998b. Rainfall infiltration and runoff from an Alfisol in semi-arid tropical India. II. Tilled systems. Soil & Tillage Research 48(1/2): 61-69.

Rao, K.P.C. 2004. The effects of management on rainfall infiltration and runoff from an Alfisol in semi-arid tropical India. http://www.icrisat.org/text/research/nrmp/researchbriefs/RBKPC.asp May 25, 2004.

Reynolds, D. and D.E. Elrick. 1986. A method for simultaneous *In-Situ* measurement in the vadose zone of field-saturated hydraulic conductivity, sorptivity, and the conductivity-pressure head relationship. Ground Water Monitoring Review 6(4):84.

Rogers, J.S., H.M. Selim, C.E. Carter, and J.L. Fouss. 1991. Variability of auger hole hydraulic conductivity values for a Commerce silt loam. Transactions of the ASAE 34(3):876-882.

RUSLE. 1997. Predicting soil erosion by water, a guide to conservation planning with revised universal soil loss equation (RUSLE). RUSLE Handbook. Published by U.S. Dept. of Agriculture, Agricultural Research Service.

Saleh, A.R., R.L. Bengtson, and J.L. Fouss. 1994. Performance of the DRAINMOD-CREAMS model with an incorporated nutrient submodel. Transactions of the ASAE 37(4):1109-1114.

SAS Institute Inc.1999. SAS User's Guide Statistics, Version 8. Cary, N.C.: SAS Institute.

Schwab, G.O., D.D. Fangmeier, W.J. Elliot, and R.K. Frevert. 1993. Other factors. Soil and Water Conservation Engineering. pp51.

Shainberg, I., G.J. Levy, P. Rengasamy, and H. Frenkel. 1992. Aggregate stability and seal formation as affected by drops' impact energy and soil amendments. Soil Science 154(2): 113-119.

Skaggs, R. W. 1978. A water management model for shallow water table soils. Report, Water Resources Research Institute of the University of North Carolina, 1978, No. 134, pp. 178.

Skaggs, R. W. 1980. Methods for design and evaluation of drainage-water management systems for soils with high water tables. Drainmod Reference Report.

Skaggs, R.W. and A. Nassehzadeh-Tabrizi. 1986. Design drainage rates for estimating drain spacings in North Carolina. Transactions of the ASAE 29(6):1631-1640.

Skaggs R.W. and G. Fernandez. 1998. DRAINMOD ver. 5 for Windows 98/NT North Calorina State University.Copyright @1980-1999.

Slattery, M.C. and R.B. Bryan. 1994. Surface seal development under simulated rainfall on an actively eroding surface. Catena 22:17-34.

Soil Survey Staff. 1992. Keys to soil taxonomy. Soil Management Support Serv. Tech. Monogr. 19. 5th ed. Pocahontas Press, Blacksberg, VA.

Southwick, L.M., T.S. Kornecki, J.L. Fouss, and B.C. Grigg. 2003. Atrazine and metolachlor in surface runoff under typical rainfall conditions in southern Louisiana. Journal of Agricultural and Food Chemistry 51(18):5355-5361.

Thomas, D.L and D.B. Beasley. 1986. A physically-based forest hydrology model I: Development and sensitivity of components. Transactions of the ASAE 29(4):962-972.

USDA. 1994. DRAINMOD user's guide. USDA Natural Resources Conservation Service.

USDA. 1998. Soil quality indicators: Infiltration. USDA Natural Resources Conservation Service. January 1998.

van Es, H.M., C.B. Ogden, R.L. Hill, R.R. Schindelbeck, and T. Tsegaye. 1999. Integrated assessment of space, time, and management-related variability of soil hydraulic properties. Soil Sci. Soc. Am. J. 63: 1599-1608.

Ward, A.D., C.A. Alexander, N.R. Fausey, and J.D. Dorsey. 1988. The ADAPT agricultural drainage and pesticide transport model. ASAE Publication, American Society of Agricultural Engineers, 1988, No. 07-88, pp. 129-141.

Williams, J.R., Y. Ouyang, J. Chen, and V. Ravi. 1998. Estimation of infiltration rate in vadose zone: application of selected mathematical models. Volume II. United States Environmental Protection Agency. National Risk Management Research Laboratory, Ada, OK 74820. EPA/600/R-97/128b. February 1998.

Willis, G.H., J.L. Fouss, J.S. Rogers, C.E. Carter, and L.M. Southwick. 1991. System design using watertable management to evaluate and control agrochemical movement in shallow-watertable soils. In Agrochemical Residue, Sampling, Design and Techniques: Soil and Groundwater, 195-211, ACS Symposium Series No. 465. R.G. Nash and A. Leslie, eds. Washington, D.C.: American Chemical Society.

Willis, G.H., L.M. Southwick, and J.L. Fouss. 1998. Nitrates in runoff and leachate from controlled-water-table plots on a Mississippi river alluvial soil. Drainage in the 21st century: food production and the environment. Proceedings of the Seventh International Drainage Symposium, Orlando, Florida, USA, 8-10 March 1998. pp.559-566.

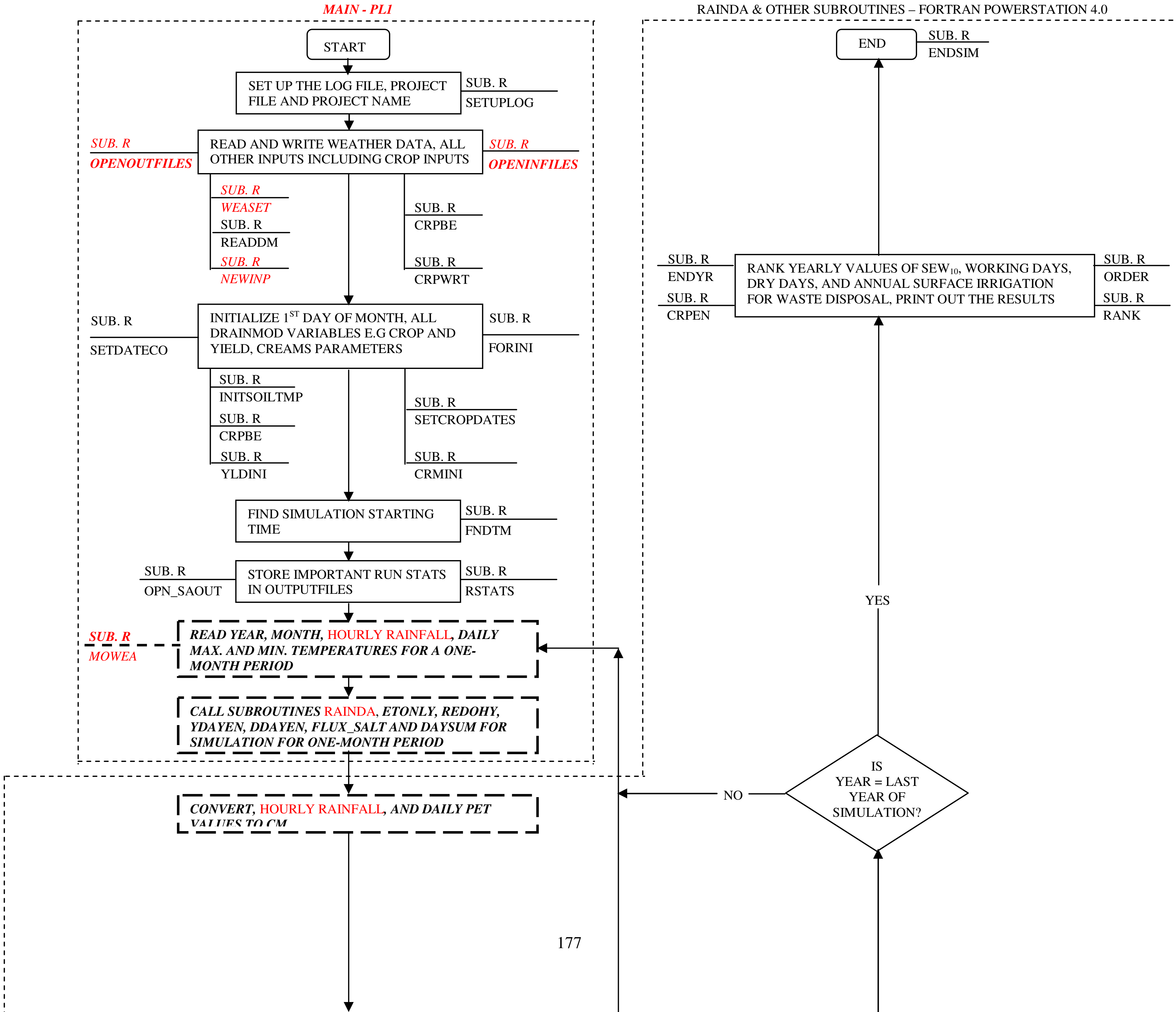
Worsham, W.E. and Sturgis M.B. 1941. Factors affecting the availability of potassium in the soils of the Lower Mississippi Deltas. Soil Sci. Soc. Proc. pp 342-347.

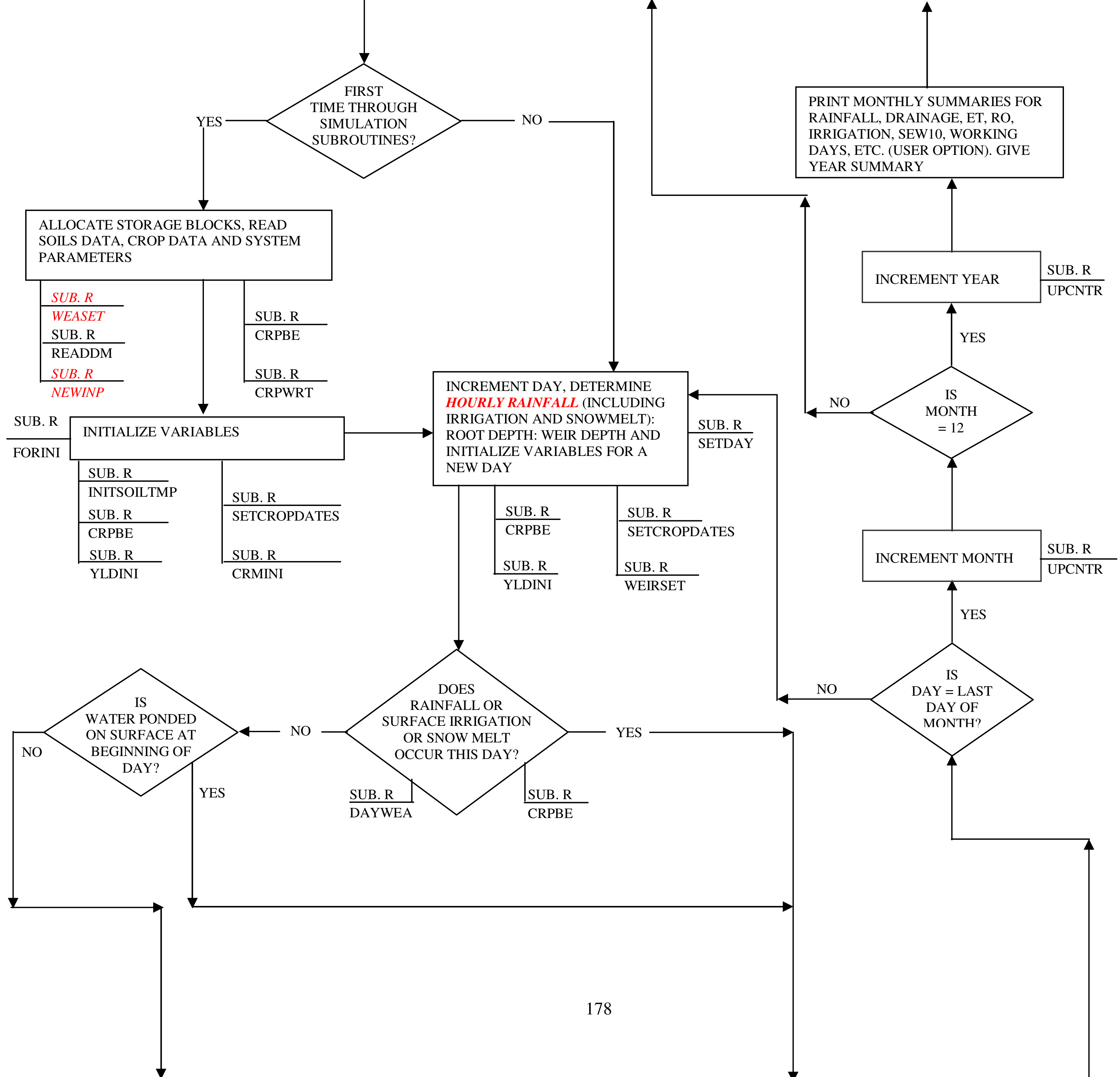
Wright, J.A., A. Shirmohmmadi, W.L. Magette, J.L. Fouss, R.L. Bengtson, and J.E. Parsons. 1992. Water table management practice effects on water quality. Transactions of the ASAE 35(3):823-831.

Zhao, S.L., S.C. Gupta, D.R. Huggins, and J.F. Moncrief. 2000. Predicting subsurface drainage, corn yield, and nitrate nitrogen losses with DRAINMOD-N. Journal of Environmental Quality 29:817-825.

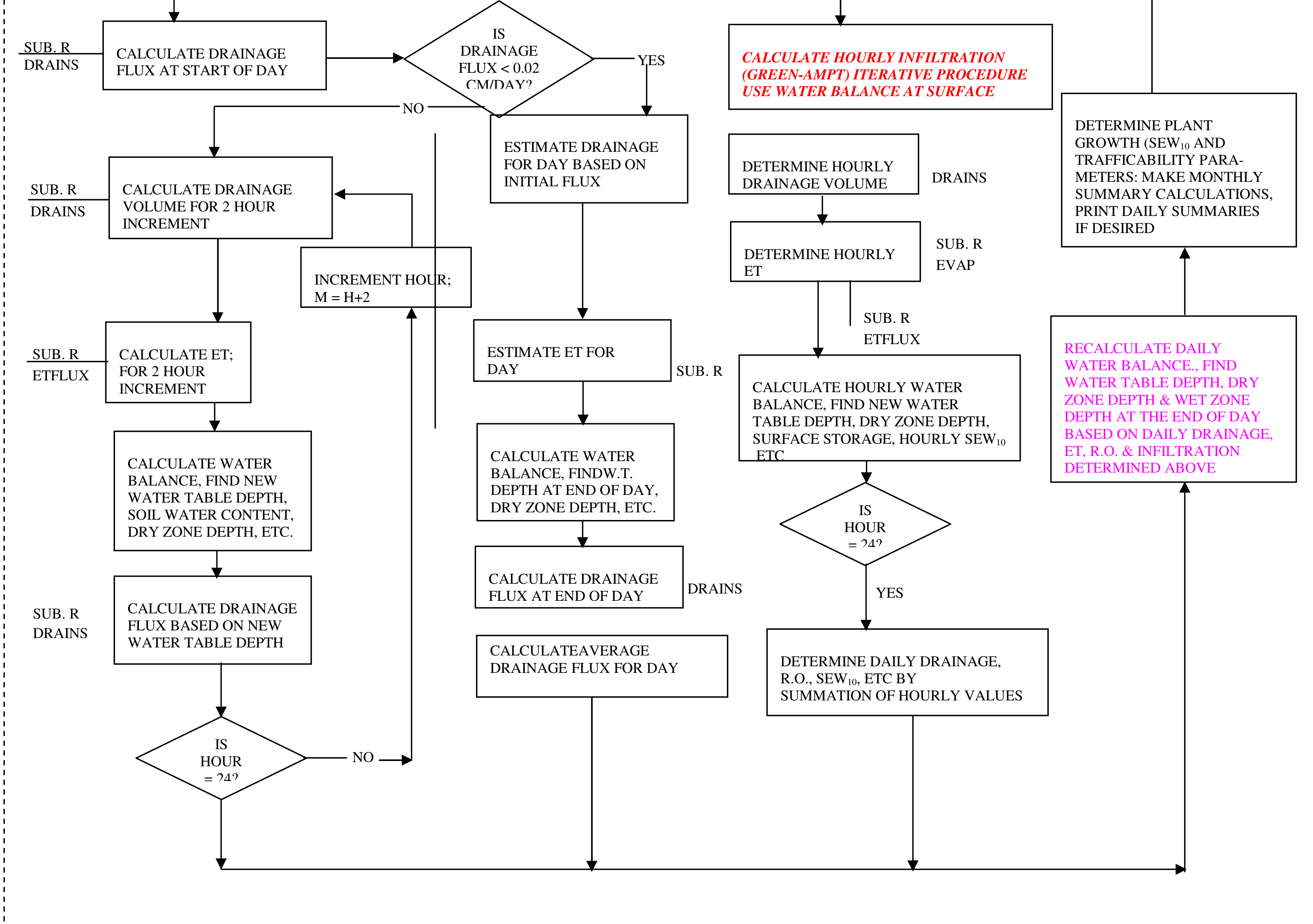
A PPENDIX A

AN ABBREVIATED GENERAL FLOW CHART FOR ORIGINAL DRAINMOD VER 5.1


MAIN - PL1
RAINDA & OTHER SUBROUTINES – FORTRAN POWERSTATION 4.0
START
SET UP THE LOG FILE, PROJECT FILE AND PROJECT NAME
SUB. R SETUPLOG
READ AND WRITE WEATHER DATA, ALL OTHER INPUTS INCLUDING CROP INPUTS
SUB. R OPENOUTFILES
SUB. R OPENINFILES
SUB. R WEASET
SUB. R READDM
SUB. R NEWINP
SUB. R CRPBE
SUB. R CRPWRT
INITIALIZE 1ST DAY OF MONTH, ALL DRAINMOD VARIABLES E.G CROP AND YIELD, CREAMS PARAMETERS
SUB. R SETDATECO
SUB. R FORINI
SUB. R INITSOILTMP
SUB. R CRPBE
SUB. R YLDINI
SUB. R SETCROPDATES
SUB. R CRMINI
FIND SIMULATION STARTING TIME
SUB. R FNDTM
STORE IMPORTANT RUN STATS IN OUTPUTFILES
SUB. R OPN_SAOUT
SUB. R RSTATS
READ YEAR, MONTH, HOURLY RAINFALL, DAILY MAX. AND MIN. TEMPERATURES FOR A ONE-MONTH PERIOD
SUB. R MOWEA
CALL SUBROUTINES RAINDA, ETONLY, REDOHY, YDAYEN, DDAYEN, FLUX_SALT AND DAYSUM FOR SIMULATION FOR ONE-MONTH PERIOD
CONVERT, HOURLY RAINFALL, AND DAILY PET VALUES TO CM
END
SUB. R ENDSIM
RANK YEARLY VALUES OF SEW10, WORKING DAYS, DRY DAYS, AND ANNUAL SURFACE IRRIGATION FOR WASTE DISPOSAL, PRINT OUT THE RESULTS
SUB. R ENDYR
SUB. R CRPEN
SUB. R ORDER
SUB. R RANK
YES
NO
IS YEAR = LAST YEAR OF SIMULATION?



FIRST TIME THROUGH SIMULATION SUBROUTINES?
YES
NO
ALLOCATE STORAGE BLOCKS, READ SOILS DATA, CROP DATA AND SYSTEM PARAMETERS
SUB. R WEASET
SUB. R READDM
SUB. R NEWINP
SUB. R CRPBE
SUB. R CRPWRT
SUB. R FORINI
INITIALIZE VARIABLES
SUB. R INITSOILTMP
SUB. R CRPBE
SUB. R YLDINI
SUB. R SETCROPDATES
SUB. R CRMINI
INCREMENT DAY, DETERMINE HOURLY RAINFALL (INCLUDING IRRIGATION AND SNOWMELT): ROOT DEPTH: WEIR DEPTH AND INITIALIZE VARIABLES FOR A NEW DAY
SUB. R SETDAY
SUB. R CRPBE
SUB. R YLDINI
SUB. R SETCROPDATES
SUB. R WEIRSET
PRINT MONTHLY SUMMARIES FOR RAINFALL, DRAINAGE, ET, RO, IRRIGATION, SEW10, WORKING DAYS, ETC. (USER OPTION). GIVE YEAR SUMMARY
INCREMENT YEAR
SUB. R UPCNTR
YES
IS MONTH = 12
NO
INCREMENT MONTH
SUB. R UPCNTR
YES
IS DAY = LAST DAY OF MONTH?
NO
DOES RAINFALL OR SURFACE IRRIGATION OR SNOW MELT OCCUR THIS DAY?
YES
NO
SUB. R DAYWEA
SUB. R CRPBE
IS WATER PONDED ON SURFACE AT BEGINNING OF DAY?
NO
YES


SUB. R DRAINS
CALCULATE DRAINAGE FLUX AT START OF DAY
IS DRAINAGE FLUX < 0.02 CM/DAY?
YES
NO
ESTIMATE DRAINAGE FOR DAY BASED ON INITIAL FLUX
CALCULATE HOURLY INFILTRATION (GREEN-AMPT) ITERATIVE PROCEDURE USE WATER BALANCE AT SURFACE
DETERMINE HOURLY DRAINAGE VOLUME
DRAINS
DETERMINE HOURLY ET
SUB. R EVAP
SUB. R ETFLUX
DETERMINE PLANT GROWTH (SEW10 AND TRAFFICABILITY PARA-METERS: MAKE MONTHLY SUMMARY CALCULATIONS, PRINT DAILY SUMMARIES IF DESIRED
SUB. R DRAINS
CALCULATE DRAINAGE VOLUME FOR 2 HOUR INCREMENT
INCREMENT HOUR; M = H+2
SUB. R ETFLUX
CALCULATE ET; FOR 2 HOUR INCREMENT
ESTIMATE ET FOR DAY
SUB. R
CALCULATE HOURLY WATER BALANCE, FIND NEW WATER TABLE DEPTH, DRY ZONE DEPTH, SURFACE STORAGE, HOURLY SEW10 ETC
RECALCULATE DAILY WATER BALANCE., FIND WATER TABLE DEPTH, DRY ZONE DEPTH & WET ZONE DEPTH AT THE END OF DAY BASED ON DAILY DRAINAGE, ET, R.O. & INFILTRATION DETERMINED ABOVE
CALCULATE WATER BALANCE, FIND NEW WATER TABLE DEPTH, SOIL WATER CONTENT, DRY ZONE DEPTH, ETC.
CALCULATE WATER BALANCE, FINDW.T. DEPTH AT END OF DAY, DRY ZONE DEPTH, ETC.
IS HOUR = 24?
CALCULATE DRAINAGE FLUX AT END OF DAY
DRAINS
YES
SUB. R DRAINS
CALCULATE DRAINAGE FLUX BASED ON NEW WATER TABLE DEPTH
CALCULATEAVERAGE DRAINAGE FLUX FOR DAY
DETERMINE DAILY DRAINAGE, R.O., SEW10, ETC BY SUMMATION OF HOURLY VALUES
IS HOUR = 24?
NO

APPENDIX B

PART OF THE MODIFIED SUBROUTINE RAINDAI TO TAKE INTO ACCOUNT RAINFALL INTENSITY

```
C*******DNM4/04*****************************************************
C-------------------------------------------------------------------
C   SUBROUTINE RAINDAI (OLD SEC 5) DETERMINES 5-MINUTE  HYDROLOGY WHEN RAIN
C   SURFACE IRRIGATION OR PONDING
C-------------------------------------------------------------------
C*GPF Added hourly water loss,weirdep & iwrset
c     SUBROUTINE RAINDA(MO,JDAY,ACCR,ICREAM,HWLOSS,WEIRDEP,IWRSET)
c   wluo     add snowmelt water    8/26/99
      SUBROUTINE RAINDAI(MO,JDAY,ACCR,Psnow,ICREAM,q_snow,avg_ice,xi,
     &      HWLOSS,WEIRDEP,IWRSET,ISOILTMP)

          INTEGER BWKDY1,BWKDY2,EWKDY1,EWKDY2
      COMMON/JFLX1/ FF(12),FFRATE(12)
      COMMON/HRPET1/ HETF(12),HET1F(12)
      COMMON/INFIL2/ DSTOR,WLO,IWET,TAV1
      COMMON/INFIL3/ DFLUXF,AVOL1F,DVOL1F,STOR2,TVOLF
      COMMON/INFIL5/ YESF,PDEBT,DEEPET,YD,HSEW
      COMMON/OLDPET/ HPET1F(12)
      COMMON/ABDT/EDTWT,AA(1000),BB(1000),A,B
      COMMON/DAY1/RVOL,WLOSS,FVOL,RO,DVOL,PUMPV,AET,SEWD,AMINC,DELTWK
      COMMON/EVAPO/PET,DDZ,ROOTD
      COMMON/INI1/TOFSIR,LRAIN,DDAY,IRRDAY,DEBT,TOTR,TOTF,TOTRO,TOTNT
      COMMON/INI2/TOTFD,TOTWF,TPUMPV,YTAV,YSUMET,WETZ,ID,YDEBT
      COMMON/INI3/AVOL,UPQ,UPVOL,UPVOL2,DELX,XNI,NI,NR1,NR2
      COMMON/POND/STOR,GEE,STORRO
      COMMON/DAYRA0/ IRAIN
C     **************************************************GMC*FIX*10/2/98
      COMMON/RAIN/RF(12),RRF(12)
C     **************************************************GMC*FIX*10/2/98
      COMMON/RAIN2/ ROFF5(12),RINFIL5(12),HDEBT5(12)
      COMMON/RDM1/IRFST,INWEIR,STMAX,DTWT,DITCHB,DITCHS
      COMMON/RDM2/ WP
      COMMON/RDM3/BWKDY1,EWKDY1,BWKDY2,EWKDY2
      COMMON/RDM4/ISEWMS,ISEWDS,ISEWME,ISEWDE,SEWX
      COMMON/WHX/WATER(1000),W(101),H(101),X(101),NN
      COMMON/FOR1/WTD(1000),VOL(1001),UPFLUX(1000)
      COMMON/SEC50/ DWRKDY,RDT,SPR
      COMMON/YIELD1/ IYIELD,IPD,JPLANT,IHARVT,TOTWRK
      COMMON/DAY2/TDVOL,SVOL,ZVOL,SLVOL
      COMMON/DAY3/TDVOL1,TDVOL2,SVOL1,SVOL2,ZVOL1,ZVOL2,SLVOL1,SLVOL2
      COMMON/VSEEP/IVSEEP,DEEPH,DEPTHV,VERTK
      COMMON/LSEEP/ILSEEP,DEPTHH,RIVERH,RIVERL,HORTK
C
      DIMENSION ACCRF(12),XI(*)
C*GPF Added array for hourly water loss,weirdep
          REAL HWLOSS(*),WEIRDEP
C*GPF 9/99 Flag for soiltemp/freeze-thaw routine
          LOGICAL ISOILTMP
C ********************************************************************
```

```
C *                         SECTION 5                          *
C * DETERMINES INFILTRATION AND CONDUCTS WATER BALANCE CALCULATIONS ON *
C * HOURLY BASIS.  ACCUMULATE TOTALS SO AT END OF SECTION 5 HAVE       *
C * ESTIMATES FOR ALL PARAMETERS FOR THE DAY.                     *
C ********************************************************************
C *           SECTION 5A - INFILTRATION CALCULATION               *
C ********************************************************************

! Initialize parameters
            slflux=0.0 !Subirrigation flux (cm/hr)
      sepflx=0.0 !Vertical deep seepage flux (cm/hr)
      zflux=0.0      !Lateral deep seepage flux (cm/hr)
  50        DTF=1.0 ! 5-minute time increments
            DDTF=0.2 !Calculate infiltration rates every minute
! and sum up infiltration every five minutes
      DTMDTF=DTF-0.01*DDTF !End minute summations after 5 minutes
            FF(1)=0.001 !Assumed infiltration after 1st 5minutes of the hour
            RVOLF=0.0      !Initialize hourly rainfall
            DO 55 N=1,12
            RVOLF=RVOLF+RF(N)
  55        CONTINUE
      I=1
      IF(FF(I).LT.0.01) THEN
        CALL SOAK(AVG_ICE) ! find parameters in Green-Ampt infiltration
                              ! equation based on effective WTD at beginning
                                                    ! of rainfall event
             ENDIF
C DETERMINES INFILTRATION CONSTANTS FOR SMALL INITIAL INFILTRATION
C INFILTRATION LOOP

  60 CALL DRAINS(DTWT,DFLUX,SLFLUX,XI,ISOILTMP)!find effective lateral
!hydraulic conductivity and compute drainage or subirrigation flux
     IF (IVSEEP.EQ.1) CALL SEEP(DTWT,SEPFLX)!determine deep vertical
!seepage losses
     IF (ILSEEP.EQ.1) CALL ZONTAL(DTWT,ZFLUX)!determine deep lateral
!seepage losses
     IF(AVOL1.LE.0.01)A=0.0 !if WTD in on the ground surface, A=0
     IF((A.LT.0.00001).AND.(DTWT.GT.0.10)) CALL SOAK(AVG_ICE) ! get
!Green-Ampt parameters
     IF(A.EQ.0.0)B=HET(J)+DFLUX+SLFLUX+SEPFLX+ZFLUX !B is set equal
!to sum of ET (HET(J), drainage (DFLUX), subirrigation (SLFLUX) and
!deep seepage rates SLFLUX,SEPFLX and ZFFLUX) and A=0 when WTD=0
     IF((A.LE.0.000001).AND.(B.LT.0.0))B=0.0
           AF=A/12             !5-minute parameters
           BF=B/12
     FFRATE(I)=AF/FF(I)+BF ! Compute five minute-infiltration rate
     IF(STOR.GT.0.0)GO TO 65      !if there is water in the depressional
!storage (ponding), then go to 65
     IF(FFRATE(I).GT.RF(I))GO TO 90 !If infiltration rate is greater
!than the rainfall rate then go to 90
  65 RAT1F=FFRATE(I) !Infiltration rate (RT1F) = infiltration capacity
!FFRATE(I)
  70 SUMF=0.0 !Time increment in infiltration calculations, 3min for
! 1 hr
     FF1=FF(I)!Infiltration rate for at start of the first 5 minutes
!within the hour
```

```
        FFT=0.0 ! Total infiltration for a given hour
C
   75 DFF=RAT1F*DDTF !Change in infiltration during time increment DDTF
      FF2=FF1+DFF !Infiltration after one minute
      RAT2F=AF/FF2+BF ! Infiltration rate after the 1st minute of DTF
      IF (STOR.LE.0.0) THEN          !If no ponding then
        IF(RAT2F.GT.RF(I)) RAT2F=RF(I) !If current infiltration rate
!is greater than rainfall rate, infiltration rate = rainfall rate
      ENDIF
      DFF=0.5*(RAT1F+RAT2F)*DDTF !Average change between one minute
!and the next minute
      SPR=STOR+RF(I)*DDTF         !Total water available for infiltration in
!time DDTF, sum of STOR +Rainfall during DDTF
      IF(DFF.GT.SPR)DFF=SPR
      FF1=FF1+DF !Sum up infiltraion
      SUM=SUM+DDTF ! Sum up the time
      RAT1F=AF/FF1+BF   ! Use the new infiltration to calculate current
!infiltration rate
      IF(STOR.LE.0.0) THEN  !If no ponding
        IF(RAT1F.GT.RF(I))RAT1F=RF(I)     ! and infiltration rate >
!rainfall  rate, infiltration rate=rainfall rate during the 5 minutes
      ENDIF
      STOR=STOR+RF(I)*DDTF-DFF !Current storage depth=Previous storage
! + Rainfall during the past minute - Infiltration during the minute
      IF(STOR.GT.STMAX)STOR=STMAX  !If storage (STOR)> maximum storage
!(STMAX), then STOR=STMAX
      IF(SUM.GE.DTMDT)GO TO 100 ! End the infiltration for 5 minutes
! Otherwise, increment to the next minute (Go to 75)
      GO TO 75
C
   90 FF1=FF(I)+RF(I)*DTF !apply equation 2-2 (Skaggs, 1980) to
! conduct a water balance at the surface for time increments of
!1 minute. The rainfall rate is used in this case to calculate
!infiltration
      RAT1F=A/FF1+B ! Use this infiltration to calculate the
!current infiltration rate after the this time increment
      IF (RAT1F.GT.RF(I)) GO TO 95 !Again if the current
! infiltration rate is greater than the current 5-minute
!rainfall rate go to 95 otherwise
      RAT1F=RF(I)             !Infiltration rate = rainfall rate
      GO TO 70 !Continue to the next 1 minute
C
   95 RAT1F=RF(I)           !Infiltration rate = rainfall rate
  100 FF(I)=FF1   !Infiltration after the jth five minute
        FFT=FFT+FF(I) !Total infiltration for hour J
!time increment
C* CREAMS CHANGES
      HDEBTF(I)=DEBT
      DVOL1F=DFLUX*DTF/12
      SVOL1F=SEPFLX*DTF/12
      ZVOL1F=ZFLUX*DTF/12
      SLVOL1F=SLFLUX*DTF/12
      TDVOL1F=DVOL1F+SVOL1F+ZVOL1F+SLVOL1F
      DVOLF=DVOLF+DVOL1F
      ZVOLF=ZVOLF+ZVOL1F
      SVOLF=SVOLF+SVOL1F
```

```
      SLVOLF=SLVOLF+SLVOL1F
      TDVOLF=DVOLF+ZVOLF+SVOLF+SLVOLF
      IF(DVOL1F.LT.0.0)PUMPV=PUMPV+DVOL1F
      IF(I.NE.1) THEN
        FVOLF=FF(I)-FF(I-1)
            ELSE
              FVOLF=FF(1)
            ENDIF

C ********************************************************************
C * SECTION 5B - WATER BALANCE CALCULATION FOR FIVE MINUTE INTERVAL       *
C ********************************************************************
C
C REEVALUATION OF WETZ,DDZ ETC
      WETZ=DTWT-DDZ
      CALL ETFLUX(AVOL1,DEBT,FVOL,TDVOL1,UPVOL2,HPET1(I),HETF(I),
            &     PDEBT)
 120  DDZ=DEBT/(WATER(1)-WP)
      IF (AVOL1.LE.0.001) THEN
        STOR=STOR-AVOL1
        IF (STOR.GT.STMAX) STOR=STMAX
        FF(I)=FF(I)+AVOL1
        FFVOL=FFVOL+AVOL1
        AVOL1=0.0
      ENDIF

      WETZ=TERPOL(AVOL1,WTD)
      IWET=WETZ+1.
      UPQ=UPFLUX(IWET)
      IF (WETZ.GT.DEEPET) UPQ=0.0
      UPVOL2=UPQ*DTF/12
            DTWT=WETZ+DDZ
            TAV1F=AVOL1+DEBT
            DSTOR=STOR-STOR2
      STOR2=STOR
      ROF(I)=RF(I)-FFVOL-DSTOR
            ROFT=ROFT+ROF(I)
            FFVOLT=FFVOL+AVOL1
            I=I+1
            IF (I.GT.12) GOTO 199 !End calculation after 5x12 minutes
            FF(I)=FF(I-1)
            IF (FF(I).LT.0.001) THEN
            FF(I)=0.001
            ENDIF
            GOTO 60

C WHEN CALCULATIONS HAVE BEEN MADE FOR 12TH 5-MINUTE INTERVAL,
C CALCULATE HOURLY INFILTRATION AND RUNOFF AND END SUBROTINE

199   CONTINUE

            RO=ROFT
            FVOL=
      RETURN
C * VARIABLE DEFINITIONS
C *   DF    : CHANGE IN INFILTRATION, CM., DURING TIME INCREMENT, DDTF.
```

```
C *   FF1    : DUMMY VARIABLE FOR FIVE MINUTE F.
C *   FF2    : DUMMY VARIABLE FOR FIVE MINUTE F.
C *   RAT1F  : DUMMY VARIABLE FOR INFILTRATION RATE - 5-MINUTE INTERVAL.
C *   RAT2F  : DUMMY VARIABLE FOR INFILTRATION RATE - 5-MINUTE INTERVAL.
C *   SPR    : TOTAL WATER AVAILABLE FOR INFILTRATION IN TIME DDTF, SUM OF
C *            STOR + RAINFALL DURING DDTF.
      END
C********DNM 4/04***************************************************************
```

APPENDIX C

GENERAL INPUT FILE - BENHURDCHIS.GEN

Note: Deep Chiseling Parameter Inputs Are Located at the Bottom of File

```
*** Job Title ***
BENHUR - CONVENTIONAL DRAINAGE (05-05-2003)
1994-2000 DRAINMOD ver. 5.1
*** Printout and Input Control ***
 1 101 C:\Drainmod\outputs
*** Climate ***
123456 C:\DIS\DRAINMOD SOURCE CODE REVISED\WEATHER\WQ9400P1.RAI
123456 C:\DIS\DRAINMOD SOURCE CODE
REVISED\WEATHER\WQPMXMN.TEM
1994  1 2000 12 3022 100 0
 1.30 1.30  .85  .75  .75  .85  .95 1.10 1.10 1.10 1.10 1.10
*** Drainage System Design ***
 1
   120.00     26.36   1500.00       .10      2.00       .50     14.12       .00
         0    0.000000E+00    0.000000E+00
         0    0.000000E+00    0.000000E+00    0.000000E+00
         0    0.000000E+00    0.000000E+00    0.000000E+00    0.000000E+00
      .50       .01       .00
 1100 1100 1100 1100 1100 1100 1100 1100 1100 1100 1100 1100
*** Soils ***
   150.00       .50
  50. 1.00  80. 4.00 120. 4.00 142. 1.00   0.  .00
99    .00
*** Trafficability ***
 3 7 7 1 720              2.0       1.3       2.0
 7 11231 719              2.0       1.3       2.0
*** Crop ***
     .261
 410 818       30.00
 410 818
14
 1 1  3.00 331  3.00 418  3.00 5 1 10.00 515 15.00 6 1 30.00 615 55.00 622 76.00
 731 90.00 8 1 25.00 815 35.00 831 50.0010 1 35.001231  3.00
*** Wastewater Irrigation ***
 0    0 0 368   1  6
 0 0       0 0       0 0       0 0
   .30000    .50000 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
WET *** Wetlands Information ***
0
  1 365
 30.0  14
```

COM *** Combo Drainage Weir Settings ***
FPE *** Fixed Avg Daily PET for the month(cm) ***

```
    .00    .00    .00    .00    .00    .00    .00    .00    .00    .00    .00    .00
```

MRA *** Monthly Ranking ***
0
FAC *** Daily PET Factors ***
0
STM *** Soil Temperature ***

```
    ZA     ZB     TKA     TKB     TB    TLAG   TSNOW   TMELT   CDEG   CICE
   .000   .000   .000   .000     .0      .0      .0      .0      .0      .0
```

Initial Soil Temperature
0
Initial snow depth(m) & density(kg/m3)

```
    .00     .00
```

Freezing characteristic curve
0
CHS *** Chiseling STMAX Parameters ***
0
1996 327 1997 327
0.012 1.25 0.10
CHK *** Chiseling Ks Parameters ***
0
1996 327 1997 327
0.03 2.0 0.50

APPENDIX D

DYNAMIC VERTICAL SATURATED HYDRAULIC CONDUCTIVITY (SETGRAMPT) SUBROUTINE SOURCE CODE

```
c      ****************************************************
c      **              INPUTS.FOR                 **
c      **          Copyright 1990 - 1991             **
c      **      North Carolina State University        **
c      ****************************************************
c
C
C INPUTS.FOR   READ ALL INPUTS INTO MODEL
C SUBROUTINES  NEWINP, PROP, READDM, READYD, ROOT, WRITYD


C*-----------------------------------------------------------------------
C* NEWINP, Subroutine
C*
C* Reads inputs from bottom of gen file
C* Convert ET from inches to cm
C*-----------------------------------------------------------------------
C* Revision History
C* Written  ?/?/??
C* Modified 3/1/97 GFernandez
C*         10/2/98 WLOU
C*-----------------------------------------------------------------------
C DNM 2/16/04 Subroutine modified to include deep chiseling
C         SUBROUTINE NEWINP(INWEIR,IFAC,MISFILE,ISOILTMP)
          SUBROUTINE NEWINP(INWEIR,IFAC,MISFILE,ISOILTMP,ICHS)
     INTEGER DAYWET
     COMMON/MRANK1/MRKIND, NYR(100),N2ET1(100),N2ET2(100),N2ET3(100),
    &         N2ET4(100),N2ET5(100),N2ET6(100),N2ET7(100),N2ET8(100),
    &         N2ET9(100),N2ET10(100),N2ET11(100),N2ET12(100)
     COMMON/RDM10/ IWCUR,NVWEIR,INDDAM(366),IWRMON(366),IWRDAY(366),
    &            DAMLEV(366)
          COMMON/WETLND/iwetld,iswett,iewett,wtdwet,daywet,twetld,
    &           consec,csecmx,iwtwet

C*DNM Deep chiseling Saturated Hydraulic conductivity parameters
C***********************CHISELINGKs************DNM  - 12/17/03**************
          COMMON/CHKs/ICHKS,aKs,Ksi,Ksf
          REAL*8 aKs,Ksi,Ksf,Ks
          INTEGER ICHKS
C***********************CHISELINGKs************DNM  - 12/17/03**************
C* Initialize chiseling parameters - DNM -01/16/04
          ICHKS=0
C* Initialize chiseling parameters - DNM -01/16/04


C******************CHISELINGKs*****************DNM - 12/07/03***
          IF (INDEX(cdummy,'CHK').gt.0) ick1=9
C***********************CHISELINGKs*************DNM - 12/07/03***

C*************Check for Ks Chiseling Parameters****DNM - 12/17/03******
```

```
      IF (ick1.eq.9) THEN
            READ(1,*)ICHKS

            IF(ICHKS.GT.0) THEN
C Check for Saturated hydraulic conductivity parameters for the chiseled field
                  READ(1,*)IYDARCS,JCHIS,IYDARCE,JCHIE
                  READ(1,*)aKs,Ksi,Ksf
            ENDIF
C Write Ks parameter inputs for the chiseled field
            IF (ICHKS.EQ.0) THEN
                  WRITE(3,6001)
            ELSE
                  WRITE(3,6002)
                  WRITE(3,6003)IYDARCS,JCHIS,IYDARCE,JCHIE,aKs,Ksi,Ksf
            ENDIF
      ENDIF

C**************Check for Ks Chiseling Parameters****DNM - 12/17/03******

C*** DNM 02/13/04************************************************
C Ks File formats
 6001   FORMAT(3x,'***** No Deep Chiseling - Ks ******',/,/)
 6002   FORMAT(3x,'***** Deep Chiseling Ks Parameters ******')
 6003 format(/,15x,'Start Year = ',i4,10x,'Start Jday = ',i4,
      1          /,15x,'End Year = ',i4,10x,'End Jday = ',i4,
    2      /,15x,'Model exponent (1/cm) =',f6.2,
      3          /,15x,'Initial Vert. Sat. Hydraulic Cond.(cm/hr) =',f6.2,
    4      /,15x,'Final Vert. Sat. Hydraulic Cond.(cm/hr) =',f6.2,/,/)
C*** DNM 02/13/04************************************************
   END


C*********************GREEN-AMPT PARAMETERS SUBROUTINE -DNM-01/20/04*******
C-------------------------------------------------------------------------
      SUBROUTINE SETGRAMPT(ICHK,JDAY,IYDARCS,JCHIS,IYDARCE,JCHIE,
      &          aKs,Ksi,Ksf,Ks,Rc,Rai,NUMA,D,E,F)

C SUBROUTINE SETGRAMPT CALCULATES THE CURRENT Ks DEPENDING ON
C CUMULATIVE RAINFALL, Rc, SINCE DEEP CHISELING OPERATION AND THEN
C GENERATES THE CURRENT TABLE OF GREEN-AMPT PARAMETERS FOR THE SIX
C LAYERS

C Variables
      REAL*8 aKs,Ksi,Ksf,Ks,Rc,Rai
      INTEGER I,ICHK,IYDARCS,JCHIS,IYDARCE,JCHIE

C Other Variables
   COMMON/ABDT/EDTWT,AA(1000),BB(1000),A,B

C*------------------VARIABLE DEFINITIONS--------------------------------DNM 01/20/04
C ICHIK---- Index determining whether chiseling;0 (no chiseling),1(chiseling)
C aKs------ Model exponent;depending on type of soil,cumulative rainfall, and type of
C          tillage operation (1/cm)
C Ksi------ Initial vertical saturated hydraulic conductivity (cm/hr)
C Ksf------ Final vertical saturated hydraulic conductivity (cm/hr)
C Ks------- Current vertical saturated hydraulic conductivity (cm/hr)
```

```
C Others--- As defined in subroutines SETMAXST,DATECO and SETRAI
C*------------------VARIABLE DEFINITIONS--------------------------------DNM 01/20/04

C Calculate Ks

                    Ks=Ksf+(Ksi-Ksf)*exp(-aKs*Rc)

                    WRITE(21,1050)
                    WRITE(21,1051)Rai,Ks

C Generation of "Current" Table for Green-Ampt parameters, which is
C dynamic (with respect to reformation of the surface seal layer)

!   Scenario one (1) for Ben Hur
                              IF (Ks.GT.1.33) THEN
                              WRITE(30,6008)
                              WRITE(30,6009)915
                              WRITE(30,6010)0.458,0.0
                              WRITE(30,6010)0.452,-10.0
                              WRITE(30,6010)0.440,-20.0
                              WRITE(30,6010)0.422,-40.0
                              WRITE(30,6010)0.402,-60.0
                              WRITE(30,6010)0.381,-100.0
                              WRITE(30,6010)0.359,-160.0
                              WRITE(30,6010)0.328,-333.3
                              WRITE(30,6010)0.312,-1000.0
                              WRITE(30,6011)0.0,0.0,1.0
                              WRITE(30,6011)10.0,0.1,0.2640
                              WRITE(30,6011)20.0,0.39,0.072
                              WRITE(30,6011)30.0,0.65,0.035
                              WRITE(30,6011)40.0,0.90,0.020
                              WRITE(30,6011)50.0,1.10,0.013
                              WRITE(30,6011)60.0,1.40,0.009
                              WRITE(30,6011)70.0,1.80,0.002
                              WRITE(30,6011)80.0,2.20,0.001
                              WRITE(30,6011)100.0,3.0,0.0
                              WRITE(30,6011)120.0,4.5,0.0
                              WRITE(30,6011)160.0,8.0,0.0
                              WRITE(30,6011)200.0,12.2,0.0
                              WRITE(30,6011)500.0,50.0,0.0
                              WRITE(30,6011)1000.0,100.0,0.0
                              WRITE(30,6006)6
                              WRITE(30,6007)0.00,0.00*Ks,Ks
                              WRITE(30,6007)30.00,1.00*Ks,Ks
                              WRITE(30,6007)60.00,2.00*1.33,1.33
                              WRITE(30,6007)120.00,2.80*1.33,1.33
                              WRITE(30,6007)150.00,4.40*0.03,0.03
                              WRITE(30,6007)500.00,4.40*0.03,0.03
                              REWIND(30) ! Overwrite the previous data in soil file

!   Scenario two (2) for Ben Hur
                              ELSE IF (Ks.LE.1.33.AND.Ks.GT.0.51) THEN
                              WRITE(30,6008)
                              WRITE(30,6009)915
                              WRITE(30,6010)0.458,0.0
                              WRITE(30,6010)0.452,-10.0
```

```
                    WRITE(30,6010)0.440,-20.0
                    WRITE(30,6010)0.422,-40.0
                    WRITE(30,6010)0.402,-60.0
                    WRITE(30,6010)0.381,-100.0
                    WRITE(30,6010)0.359,-160.0
                    WRITE(30,6010)0.328,-333.3
                    WRITE(30,6010)0.312,-1000.0
                    WRITE(30,6011)0.0,0.0,1.0
                    WRITE(30,6011)10.0,0.1,0.2640
                    WRITE(30,6011)20.0,0.39,0.072
                    WRITE(30,6011)30.0,0.65,0.035
                    WRITE(30,6011)40.0,0.90,0.020
                    WRITE(30,6011)50.0,1.10,0.013
                    WRITE(30,6011)60.0,1.40,0.009
                    WRITE(30,6011)70.0,1.80,0.002
                    WRITE(30,6011)80.0,2.20,0.001
                    WRITE(30,6011)100.0,3.0,0.0
                    WRITE(30,6011)120.0,4.5,0.0
                    WRITE(30,6011)160.0,8.0,0.0
                    WRITE(30,6011)200.0,12.2,0.0
                    WRITE(30,6011)500.0,50.0,0.0
                    WRITE(30,6011)1000.0,100.0,0.0
                    WRITE(30,6006) 6
                    WRITE(30,6007)   0.00,0.00*Ks,Ks
                    WRITE(30,6007)  30.00,1.00*Ks,Ks
                    WRITE(30,6007)  60.00,2.00*Ks,Ks
                    WRITE(30,6007) 120.00,2.80*Ks,Ks
                    WRITE(30,6007) 150.00,4.40*Ks,Ks
                    WRITE(30,6007) 500.00,4.40*Ks,Ks
                    REWIND(30) ! Overwrite the previous data in soil file

!   Scenario three (3) for Ben Hur
!   Use the original .SIN data file .. no more benefits of chiseling
                    ELSE
                    WRITE(30,6008)
                    WRITE(30,6009)915
                    WRITE(30,6010)0.458,0.0
                    WRITE(30,6010)0.452,-10.0
                    WRITE(30,6010)0.440,-20.0
                    WRITE(30,6010)0.422,-40.0
                    WRITE(30,6010)0.402,-60.0
                    WRITE(30,6010)0.381,-100.0
                    WRITE(30,6010)0.359,-160.0
                    WRITE(30,6010)0.328,-333.3
                    WRITE(30,6010)0.312,-1000.0
                    WRITE(30,6011)0.0,0.0,1.0
                    WRITE(30,6011)10.0,0.1,0.2640
                    WRITE(30,6011)20.0,0.39,0.072
                    WRITE(30,6011)30.0,0.65,0.035
                    WRITE(30,6011)40.0,0.90,0.020
                    WRITE(30,6011)50.0,1.10,0.013
                    WRITE(30,6011)60.0,1.40,0.009
                    WRITE(30,6011)70.0,1.80,0.002
                    WRITE(30,6011)80.0,2.20,0.001
                    WRITE(30,6011)100.0,3.0,0.0
                    WRITE(30,6011)120.0,4.5,0.0
```

```
                        WRITE(30,6011)160.0,8.0,0.0
                        WRITE(30,6011)200.0,12.2,0.0
                        WRITE(30,6011)500.0,50.0,0.0
                        WRITE(30,6011)1000.0,100.0,0.0
                        WRITE(30,6006) 6
                        WRITE(30,6007)   0.00,0.00*0.40,0.40
                        WRITE(30,6007)  30.00,1.00*0.40,0.40
                        WRITE(30,6007)  60.00,2.00*0.40,0.40
                        WRITE(30,6007) 120.00,2.80*0.40,0.40
                        WRITE(30,6007) 150.00,4.40*0.40,0.40
                        WRITE(30,6007) 500.00,4.40*0.40,0.40
                        REWIND(30) ! Overwrite the previous data in soil file
                        ENDIF

C Read in infiltration constants for Green-Ampt equation and interpolate

        CALL PROPC

        RETURN

C* Output file formats
 1050 FORMAT(///'TODAYS RAIN',8X,'CURRENT Ks'/
    $4X,'(CM)',12X,'(CM/HR)')
 1051   FORMAT(F8.2,12X,F5.2)
C* .SIN file formats
 6003 FORMAT('Rc',3x,'Ks')
 6004 FORMAT(f4.2,3x,f3.2)
 6006 FORMAT(i2)
 6007 FORMAT(f10.2,f10.2,f10.2)
 6008   FORMAT('BENHURDC.SIN')
 6009 FORMAT(1x,i3)
 6010   FORMAT(f10.7,f10.1)
 6011 FORMAT(f10.4,f10.4,f10.4)

        END
C------------------------------------------------------------------------

C-----------------------DNM 04/04------------------------------------------------
      SUBROUTINE PROPC
C ************************************************************************
C * THIS SUBROUTINE WAS A MODIFICATION OF SUBROUTINE PROP AND IT READS
C * IN A TABLE OF CONSTANTS FOR THE GREEN - AMPT INFILTRATION EQUATION
C * FOR VARIOUS WATER TABLE DEPTHS AND INTERPOLATES THEM.
C * ALL GREEN-AMPT PROPERTIES ARE STORED IN ARRAYS SO THAT THEY CAN BE
C * EASILY RECALLED KNOWING THE WATER TABLE DEPTH.
C ************************************************************************
C
C READ SOIL PROPERTIES AND STORE THE INFORMATION INTO
C PROPER ARRAYS BY INTERPOLATION
      COMMON/ABDT/EDTWT,AA(1000),BB(1000),A,B
      COMMON/FOR1/WTD(1000),VOL(1001),UPFLUX(1000)
      COMMON/WHX/WATER(1000),W(101),H(101),X(101),NN
      REAL THETA(50),HEAD(50)
      REAL D(10),E(10),F(10)
      REAL AIA(1000),BIB(1000)
      REAL XVOL(100)
```

```
      REAL FLUX(100)
           REAL VOLX(1001)
C*GPF 7/97 Error log
      COMMON/ERRLOG/ ERRSUB,ERRVAR
      CHARACTER*24 ERRSUB
      CHARACTER*64 ERRVAR
      INTEGER DAYWET
C*****************************************************DNM-01/20/04***
      CHARACTER*(50) MISFILE
C*****************************************************DNM-01/20/04***
C |-------------------------------------------------------------------
C | THE FOLLOWING SECTION READS IN SOIL WATER CHARACTERISTIC, AND CAL-
C | CULATES RELATIONSHIP BETWEEN DRAINED VOLUME AND WATER TABLE DEPTH.
C |-------------------------------------------------------------------
C
      ERRSUB = 'PROP'
      ERRVAR = 'SOIL WATER CHARACTERISTICS'

      READ(30,'(1X)')
      READ(30,900) NUM,IVREAD
      READ(30,905)(THETA(I),HEAD(I),I=1,NUM)
cccc debug stuff
C     DATA READ IN ORDER OF DECREASING WATER CONTENT
      DO 5 I = 1,NUM
    5 HEAD(I) = -HEAD(I)+1.0
      I=1
      WATER(1)=THETA(1)
      P=WATER(1)
      VOL(1)=0
      DO 10 J = 2,1000
      AJ = J
      IF(AJ.GT.HEAD(I+1))I=I+1
      AI = I
      AIM=I-1
      WATER(J) = THETA(I)+(AJ-HEAD(I))/(HEAD(I+1)-HEAD(I))*
     &(THETA(I+1)-THETA(I))
      AVG = (WATER(J)+WATER(J-1))/2
      VOL(J) = VOL(J-1) + P-AVG
   10 CONTINUE
C
C |-------------------------------------------------------------------
C | THE FOLLOWING READS TABULAR VALUES FOR W.T. DEPTH VS. DRAINAGE VOLUM
C | AND UPWARD FLUX.
C | THE NUMBER OF VALUES READ IS IVREAD.
C | IF IVREAD .LE. 0, USE ABOVE W.T.D.-VOL. RELATIONSHIP AND CRITICAL
C | DEPTH CONCEPT FOR UPWARD FLUX.
C |-------------------------------------------------------------------
C
      ERRVAR = 'DRAINED VOLUME-WATER TABLE-UPWARD FLUX'
      IF(IVREAD.LE.0) GO TO 14
C      IF WATER VOL VS. WATER TAB DEPTH IS READ IN GO TO NEXT STEPS
      READ(30,930)(X(I),XVOL(I),FLUX(I),I=1,IVREAD)
      IF (X(IVREAD).LT.1000.0 .OR. XVOL(IVREAD).LT.100.0) THEN
        X(IVREAD) = 1000.0
        XVOL(IVREAD) = 100.0
        FLUX(IVREAD) = 0.0
```

```
      ENDIF

      DO 12 I=1,IVREAD
   12 X(I)=X(I)+1.0
      UPFLUX(1)=FLUX(1)
      VOL(1)=XVOL(1)
      I=1
      DO 11 L=2,1000
      XL=L
      IF(XL.GT.X(I+1)) I=I+1
      XI=I
      XIM=XI-1.
C/****
C/* ADDED XIRATI TO TRY AND FIX PROBLEM OF REPEATED VALS
      XIRATI=(XL-X(I))/(X(I+1)-X(I))
      UPFLUX(L)=FLUX(I)+XIRATI*(FLUX(I+1)-FLUX(I))
   11 VOL(L)=XVOL(I)+XIRATI*(XVOL(I+1)-XVOL(I))
C
C |--------------------------------------------------------------------
C | CONVERT TO ARRAY SO CAN DIRECTLY DETERMINE WATER TABLE DEPTH (OR WET
C | ZONE DEPTH) IF KNOW AIR VOLUME.
C |--------------------------------------------------------------------
C
   14 CONTINUE
      DO K = 1,1000
        VOLX(K) = VOL(K)
        VOL(K) = VOL(K)*10.0+1.0
      ENDDO
      I = 2
      AI = I
      WTD(1) = 0
      DO 25 L = 2,1000
      AL = L
      ALM = AL-1.0
      IF(VOL(L).LT.AI) GO TO 25
C/********
C/* FIX FOR EQUAL VOLUMES, 5/89, JEP
C/********
   20 IF (VOL(L).EQ.VOL(L-1)) THEN
        WTD(I) = ALM
      ELSE
        WTD(I) = ALM + (AI-VOL(L-1))/(VOL(L)-VOL(L-1))-1.0
      ENDIF
      I = I + 1
      AI = I
      IF(VOL(L).GT.AI) GO TO 20
   25 CONTINUE

      DO 30 I=1,1000
      VOL(I) = 0.1*(VOL(I)-1.0)
      XI = I
      AI = 0.1*(XI-1.0)
      BI = I-1
      AIA(I)=AI
      BIB(I)=BI
   30 CONTINUE
```

```
C |-------------------------------------------------------------------
C | READ IN INFILTRATION CONSTANTS FOR GREEN-AMPT EQUATION AND INTERPOLA
C |-------------------------------------------------------------------
      ERRVAR = 'INFILTRATION'
      READ(30,900)NUMA
      READ(30,920)(D(I),E(I),F(I),I=1,NUMA)
            REWIND(30)      !Set the soil file to start at the beginning DNM 3/04
      IF(D(NUMA).GE.1000.) GO TO 160
      NUMA=NUMA+1
      D(NUMA)=1000.
      E(NUMA)=E(NUMA-1)
      F(NUMA)=F(NUMA-1)
  160 WRITE(21,940)
      WRITE(21,945) (D(I),E(I),F(I),I=1,NUMA)
      AA(1)=0.
      BB(1)=0.
      I=1
      J=2
      XJ=J-1
   35 IP=I+1
      RATIO=(XJ-D(I))/(D(IP)-D(I))
      AA(J)=E(I)+RATIO*(E(IP)-E(I))
      BB(J)=F(I)+RATIO*(F(IP)-F(I))
      J=J+1
      XJ=J-1
      IF (XJ.GT.D(IP))I=I+1
      IF(I.GE.NUMA)GO TO 45
      IF(J.GT.1000)GO TO 45
      GO TO 35
   45 CONTINUE
  900 FORMAT(2I2)
  905 FORMAT(F10.7,F10.1)
  920 FORMAT(3F10.2)
  930 FORMAT(3F10.4)
  940 FORMAT(12X,'CURRENT GREEN AMPT INFILTRATION PARAMETERS TABLE'
     $ /22X,'W.T.D.',9X,'A',9X,'B'/23X,'(CM)',6X,'(CM^2/HR)',2X,
     $'(CM/HR)')
  945 FORMAT(17X,3F11.3)
C ***********************************************************************
      RETURN
      END

C------------------------DNM 04/04-------------------------------------
```

APPENDIX E

DYNAMIC MAXIMUM SURFACE DEPRESSIONAL STORAGE (SETMAXST) SUBROUTINE SOURCE CODE

```
c      ****************************************************
c      **              INPUTS.FOR                **
c      **          Copyright 1990 - 1991            **
c      **      North Carolina State University        **
c      ****************************************************
c
C
C INPUTS.FOR   READ ALL INPUTS INTO MODEL
C SUBROUTINES  NEWINP, PROP, READDM, READYD, ROOT, WRITYD


C*------------------------------------------------------------------------
C* NEWINP, Subroutine
C*
C* Reads inputs from bottom of gen file
C* Convert ET from inches to cm
C*------------------------------------------------------------------------
C* Revision History
C* Written  ?/?/??
C* Modified 3/1/97 GFernandez
C*         10/2/98 WLOU
C*------------------------------------------------------------------------
C DNM 2/16/04 Subroutine modified to include deep chiseling
C         SUBROUTINE NEWINP(INWEIR,IFAC,MISFILE,ISOILTMP)
          SUBROUTINE NEWINP(INWEIR,IFAC,MISFILE,ISOILTMP,ICHS)
      INTEGER DAYWET
      COMMON/MRANK1/MRKIND,NYR(100),N2ET1(100),N2ET2(100),N2ET3(100),
     &         N2ET4(100),N2ET5(100),N2ET6(100),N2ET7(100),N2ET8(100),
     &         N2ET9(100),N2ET10(100),N2ET11(100),N2ET12(100)
      COMMON/RDM10/ IWCUR,NVWEIR,INDDAM(366),IWRMON(366),IWRDAY(366),
     &            DAMLEV(366)
          COMMON/WETLND/iwetld,iswett,iewett,wtdwet,daywet,twetld,
     &           consec,csecmx,iwtwet
C*DNM Deep chiseling STMAX parameters
C***********************CHISELINGSTMAX**********DNM  - 12/04/03**************
          COMMON/CHSTMAX/ICHIS,IYDARCS,JCHIS,IYDARCE,JCHIE,
          &                              AMaxs,MAXSTI,MAXSTF
          REAL*8 AMaxs,MAXSTI,MAXSTF,MAXST,STMAXC
          INTEGER ICHS,DCHI,IYDARCS,IYDARCE,JCHIE,JDAY,NCHI,JCHIS
          INTEGER ILEAP,IYCS,IYCE,NYS,NLYS,LYS,YCS
C***********************CHISELINGSTMAX**********DNM  - 12/04/03**************

C* Initialize chiseling parameters - DNM -01/16/04
          ICHS=0
C* Initialize chiseling parameters - DNM -01/16/04

C*******************CHISELINGSTMAX***************DNM - 11/14/03***
          IF (INDEX(cdummy,'CHS').gt.0) ick1=8
C***********************CHISELINGSTMAX***********DNM - 11/14/03***
C**************Check for STMAX Chiseling Parameters****DNM - 12/15/03***
```

```
      IF (ick1.eq.8) THEN
              READ(1,*)ICHS
              IF(ICHS.gt.0) THEN
C Read MAXIST parameters for the chiseled field
                      READ(1,*)IYDARCS,JCHIS,IYDARCE,JCHIE
                      READ(1,*)Amaxs,MAXSTI,MAXSTF
              ENDIF
C Write STMAX parameter inputs for the chiseled field
              IF (ICHS.eq.0) THEN
              WRITE(3,5001)
              ELSE
              WRITE(3,5002)
              WRITE(3,5003)IYDARCS,JCHIS,IYDARCE,JCHIE,Amaxs,MAXSTI,MAXSTF
              ENDIF
      ENDIF
C*************Check for STMAX Chiseling Parameters****DNM - 12/15/03***

C*** DNM 02/13/04***********************************************
C STMAX File formats
 5001   FORMAT(3x,'***** No Deep Chiseling - STMAX ******',/,/)
 5002   FORMAT(3x,'***** Deep Chiseling STMAX Parameters ******')
 5003 format(/,15x,'Start Year = ',i4,10x,'Start Jday = ',i4,
      1          /,15x,'End Year = ',i4,10x,'End Jday = ',i4,
    2      /,15x,'Model exponent (1/day) =',f6.3,
      3          /,15x,'Initial Maximum Dep. Storage (cm) =',f6.2,
    4      /,15x,'Final Maximum Dep. Storage (cm) =',f6.2,/,/)
C*** DNM 02/13/04***********************************************
   END

C-----------------------------------------------------------------------
C**************************NEW STMAX SUBROUTINE -DNM-01/16/04**************
C-----------------------------------------------------------------------
C SUBROUTINE SETMAXST CALCULATES THE CURRENT STMAX DEPENDING ON NUMBER
C OF DAYS AFTER DEEP CHISELING

      SUBROUTINE SETMAXST(ICHS,JDAY,IYDARCS,JCHIS,IYDARCE,JCHIE,DCHI,
      &             NCHI,AMaxs,MAXSTI,MAXSTF,MAXST,STMAXC)

C Variables
      REAL*8 AMaxs,MAXSTI,MAXSTF,MAXST,STMAXC
      INTEGER ICHS,DCHI,IYDARCS,JCHIS,IYDARCE,JCHIE,JDAY,NCHI,IYDARC
      INTEGER ILEAP,IYCS,IYCE,NYS,NLYS,LYS,YCS

C*-----------------VARIABLE DEFINITIONS------------------------------DNM 01/14/04
C ICHIS---- Index determining whether chiseling;0 (no chiseling),1(chiseling)
C IYDARCS-- Year when chiseling was started
C JCHIS---- Julian date when chiseling was done
C IYDARCE-- Year when chiseling ended;just before next chiseling operation
C JCHIE---- Julian date when chiseling ended;just before next chiseling operation
C DCHI----- Number of days since chiseling was carried out
C NCHI----- Total number of days between two chiseling operations
C AMaxs---- Model exponent;depending on the number of days between chiseling
C         operations and the type of soil (1/day)
C MAXSTI--- Initial (starting) maximum surface depressional storage (cm)
C MAXSTF--- Final maximum surface depressional storage (cm)
C MAXST---- Current maximum surface depressional storage (cm)
```

```
C IYCS----- Dummy variable for year when chiseling was started
C IYCS----- Dummy variable for year when chiseling ended
C NYS------ Number of years between IYDARCS and IYDARCE
C NLYS----- Number of non leap years between IYDARCS and IYDARCE
C LYS-------Number of leap years between IYDARCS and IYDARCE
C YCS------ Temporary variable representing if chiseling starting year
C          is leap or not
C STMAXC--- Dynamic STMAX when chiseling is carried out (cm)
C*------------------VARIABLE DEFINITIONS--------------------------------DNM 01/14/04

! Determine whether the year chiseling was done is leap or not

      IF ((IYDARCS/4*4-IYDARCS).EQ.0) THEN
      ILEAP=1            ! Leap year (366 days)
      YCS=1 ! Leap year (366 days)
      ELSE
      ILEAP=0            ! Non leap year (365 days)
      YCS=0 ! Non leap year (365 days)
      ENDIF

! NYS, Number of years between the year chiseling was done and
!year chiseling ended (just before next chiseling commenced)

      NYS=IYDARCE-IYDARCS-1

C Initialize number of normal and leap years between starting and
C and ending chiseling years

      NLYS=0
      LYS=0

C Check whether the subsequent years between the chiseling proces are
C leap or not and sum the number of leap (LYS) and non-leap
C (NLYS) years

   IF (NYS.LE.0) THEN
       NLYS=NLYS+0
       LYS=LYS+0
      ELSE
      IYDARC=IYDARCS
       DO 20 I=1,NYS
             IYDARC=IYDARC+1
             IF ((IYDARC/4*4-IYDARC).EQ.0) THEN
             ILEAP=1
             LYS=LYS+1 !Number of leap years
             ELSE
             ILEAP=0
             NLYS=NLYS+1   !Number of regular years
             ENDIF
20    CONTINUE
      ENDIF

C Calculate NCHI

      IF (NYS.LT.0) THEN
             NCHI=JCHIE-JCHIS
```

```
      ELSE IF ((NYS.GE.0).AND.(YCS.EQ.0)) THEN
            NCHI=(365-JCHIS)+NLYS*365+LYS*366+JCHIE
      ELSE IF ((NYS.GE.0).AND.(YCS.EQ.1)) THEN
            NCHI=(366-JCHIS)+NLYS*365+LYS*366+JCHIE
      ENDIF
Calculate DCHI and STMAXC

      MAXST=MAXSTF+(MAXSTI-MAXSTF)*EXP(-Amaxs*DCHI)
      STMAXC=MAXST

      RETURN

C File formats
 5001   FORMAT(2(i4,2x,i2))
 5002 FORMAT(/,15x,'No.of Days Between Chiseling Events = ',i4,/)
 5003 FORMAT(15x,'ABORTED IN SETMAXST',/,
    *15x,'CHISELING ENDING YEAR 'I4,' COULD NOT BE',
    *' FOUND.',/,15x,'LAST YEAR READ WAS ',I4)
 5004 FORMAT(30x,i4,31x,f6.2)
 5005 FORMAT(15x,'No. of Days Since Chiseling',10x,'STMAXC (cm)',
      1        /,15x,'********************************',10x,'***********')
 5006 FORMAT(15x,'',/)

      END
C-----------------------------------------------------------------------
```

APPENDIX F

THE ORIGINAL DRAINMOD MODEL AND THE MODIFIED DRAINMOD MODELS VALIDATION DATA

Measured and DRAINMOD-K_s model predicted runoff for the period between– 9/28/1995 to 11/21/1996 (Only days with runoff were included)

Date	Rainfall (cm)	Measured runoff (cm)	DRAINMOD-K_s predicted runoff (cm)
10/3/95	4.52	0.039	0.949
10/13/95	2.62	0.007	0
10/14/95	2.95	0.268	0.961
10/31/95	0.1	0.034	0
11/1/95	0.2	0.049	0
11/2/95	14.78	12.011	9.991
11/3/95	1.02	1.118	0.454
12/7/95	3.91	0.000	0.584
12/8/95	11.76	0.000	10.255
1/26/96	4.8	0.000	1.42
1/27/96	0	5.078	0
1/28/96	0	0.063	0
2/28/96	6.38	0.000	1.21
3/31/96	4.39	4.427	0.364
4/1/96	0.08	0.039	0
4/6/96	0	0.511	0
4/12/96	0	0.011	0
4/13/96	0.69	8.527	0
4/14/96	7.11	3.343	3.133
4/15/96	2.62	0.010	0.238
4/23/96	0	1.490	0
4/24/96	2.21	0.000	0
4/29/96	0	2.159	0
5/9/96	5.36	2.210	1.501
5/11/96	0	0.077	0
6/8/96	2.77	0.000	0.004
7/17/96	5.49	0.000	2.199
8/11/96	3.02	0.000	0.595
8/13/96	3	0.000	0.293
8/28/96	2.62	0.000	0.574
9/21/96	4.09	0.000	0.908
9/28/96	3.45	0.000	0.015
10/26/96	13.61	0.000	9.487
10/27/96	7.9	0.000	6.315
11/8/96	3.51	0.000	1.306
Total	187.650	41.527	52.756
tTest			0.650837

Measured and DRAINMOD-K_s model predicted runoff for the period between–11/22/1996 to 11/22/1997 (Only days with runoff were included)

Date	Rainfall (cm)	Measured runoff (cm)	DRAINMOD-Ks predicted runoff (cm)
12/20/96	3.25	0.000	0.186
12/31/96	0	0.004	0
2/12/97	5.94	0.000	2
2/24/97	5.56	0.000	1.221
2/25/97	2.59	0.000	1.202
4/5/97	4.55	0.000	0.638
4/26/97	5.49	1.668	0.446
4/27/97	6.63	7.505	4.808
4/28/97	0.03	0.051	0
5/3/97	2.39	0.844	0
5/15/97	2.24	0.062	0
5/21/97	2.29	0.526	0
5/22/97	4.39	4.953	1.235
5/23/97	0.43	0.080	0
5/24/97	3.4	4.532	0.581
5/25/97	0.18	0.264	0
5/28/97	1.55	0.388	0
5/29/97	0.15	0.011	0
5/31/97	2.29	2.667	0.191
6/5/97	0.03	0.000	0
6/6/97	5.41	1.290	3.079
6/7/97	0	0.025	0
6/8/97	0.03	0.025	0
6/9/97	0.03	0.025	0
6/17/97	12.19	8.011	4.532
6/18/97	6.93	0.000	5.725
6/19/97	0.79	0.135	0
6/26/97	3.76	2.229	1.287
6/28/97	1.3	0.120	0
7/5/97	0	0.026	0
7/9/97	1.6	0.023	0
7/29/97	2.62	0.000	0.085
7/31/97	5.11	0.507	1.699
8/7/97	3.35	0.021	0.563
8/8/97	1.9	0.392	0
8/20/97	5.21	3.169	2.236
8/21/97	0.05	0.019	0
10/24/97	5.87	0.007	1.597
11/12/97	6.4	2.479	1.989
11/21/97	3.94	4.174	1.29
11/22/97	0	0.003	0
Total		46.237	36.590
tTest			0.58

Measured and DRAINMOD-STMAX model predicted runoff for the period between–9/28/1995 to 11/21/1996 (Only days with runoff were included)

Date	Rainfall (cm)	Measured runoff (cm)	DRAINMOD-STMAX predicted runoff (cm)
10/3/95	4.52	0.039	0.78
10/13/95	2.62	0.007	0
10/14/95	2.95	0.268	0.398
10/31/95	0.1	0.034	0
11/1/95	0.2	0.049	0
11/2/95	14.78	12.011	9.266
11/3/95	1.02	1.118	0.463
11/4/95	0	0.025	0
11/5/95	0.25	0.000	0
11/6/95	0	0.002	0
12/7/95	3.91	0.000	0.129
12/8/95	11.76	0.000	10.079
1/25/96	0	0.022	0
1/26/96	4.8	0.000	1.834
1/27/96	0	5.078	0
1/28/96	0	0.063	0
2/28/96	6.38	0.000	1.166
3/31/96	4.39	4.427	0.993
4/1/96	0.08	0.039	0
4/5/96	0	0.001	0
4/6/96	0	0.511	0
4/12/96	0	0.011	0
4/13/96	0.69	8.527	0
4/14/96	7.11	3.343	3.838
4/15/96	2.62	0.010	0.432
4/23/96	0	1.490	0
4/24/96	2.21	0.000	0
4/29/96	0	2.159	0
4/30/96	1.78	0.000	0.026
5/9/96	5.36	2.210	2.146
5/11/96	0	0.077	0
6/8/96	2.77	0.000	0.252
6/25/96	2.34	0.000	0.007
7/17/96	5.49	0.000	2.543
8/11/96	3.02	0.000	0.856
8/12/96	1.78	0.000	0.046
8/13/96	3	0.000	0.519
8/28/96	2.62	0.000	0.794
9/21/96	4.09	0.000	1.145
9/28/96	3.45	0.000	0.157
10/25/96	1.9	0.000	0.055
10/26/96	13.61	0.000	9.589
10/27/96	7.9	0.000	6.176
11/8/96	3.51	0.000	1.298
Total		41.521	54.987
tTest			0.57

Measured and DRAINMOD-STMAX model predicted runoff for the period between– 11/22/1996 to 11/22/1997 (Only days with runoff were included)

Date	Rainfall (cm)	Measured runoff (cm)	DRAINMOD-STMAX predicted runoff(cm)
12/31/96	0	0.004	0
2/12/97	5.94	0.000	1.578
2/13/97	0.05	0.000	0.004
2/24/97	5.56	0.000	0.857
2/25/97	2.59	0.000	1.16
4/5/97	4.55	0.000	1.118
4/26/97	5.49	1.668	0.996
4/27/97	6.63	7.505	4.438
4/28/97	0.03	0.051	0
5/3/97	2.39	0.844	0.021
5/15/97	2.24	0.062	0
5/21/97	2.29	0.526	0
5/22/97	4.39	4.953	1.56
5/23/97	0.43	0.080	0
5/24/97	3.4	4.532	0.38
5/25/97	0.18	0.264	0
5/28/97	1.55	0.388	0
5/29/97	0.15	0.011	0
5/31/97	2.29	2.667	0.385
6/6/97	5.41	1.290	3.396
6/7/97	0	0.025	0
6/8/97	0.03	0.025	0
6/9/97	0.03	0.025	0
6/17/97	12.19	8.011	5.083
6/18/97	6.93	0.000	5.254
6/19/97	0.79	0.135	0
6/26/97	3.76	2.229	1.513
6/28/97	1.3	0.120	0
7/5/97	0	0.026	0
7/9/97	1.6	0.023	0
7/29/97	2.62	0.000	0.238
7/31/97	5.11	0.507	1.902
8/7/97	3.35	0.021	0.729
8/8/97	1.9	0.392	0
8/20/97	5.21	3.169	2.461
8/21/97	0.05	0.019	0
8/31/97	1.9	0.000	0.096
9/6/97	1.98	0.000	0.097
10/24/97	5.87	0.007	2.133
11/12/97	6.4	2.479	1.973
11/21/97	3.94	4.174	1.276
11/22/97	0	0.003	0
Total		46.236	38.648
tTest			0.64

Measured and DRAINMOD-ORIGINAL and DRAINMOD-Ks-STMAX models predicted runoff for the period between– 9/28/1995 to 11/21/1997 (Only days with runoff were included)

Date	Rain (cm)	M RO (cm)	DRAINMOD-O RO (cm)	DRAINMOD-K_s-STMAX RO(cm)
10/2/95	2.01	0.000	0.071	0
10/3/95	4.52	0.039	1.848	0
10/13/95	2.62	0.007	0.251	0
10/14/95	2.95	0.268	1.096	0.033
10/31/95	0.1	0.034	0	0
11/1/95	0.2	0.049	0	0
11/2/95	14.78	12.011	10.068	9.249
11/3/95	1.02	1.118	0.454	0.463
11/4/95	0	0.025	0	0
11/5/95	0.25	0.000	0	0
11/6/95	0	0.002	0	0
12/6/95	2.9	0.000	0.487	0
12/7/95	3.91	0.000	0.595	0.089
12/8/95	11.76	0.000	9.954	10.084
1/24/96	1.68	0.000	0.232	0
1/25/96	0	0.022	0	0
1/26/96	4.8	0.000	2.101	1.148
1/27/96	0	5.078	0	0
1/28/96	0	0.063	0	0
2/28/96	6.38	0.000	1.509	1.027
3/31/96	4.39	4.427	1.118	0.239
4/1/96	0.08	0.039	0	0
4/5/96	0	0.001	0	0
4/6/96	0	0.511	0	0
4/12/96	0	0.011	0	0
4/13/96	0.69	8.527	0	0
4/14/96	7.11	3.343	3.944	3.028
4/15/96	2.62	0.010	0.533	0.137
4/23/96	0	1.490	0	0
4/24/96	2.21	0.000	0.078	0
4/29/96	0	2.159	0	0
4/30/96	1.78	0.000	0.111	0
5/9/96	5.36	2.210	2.208	1.423
5/11/96	0	0.077	0	0
6/8/96	2.77	0.000	0.306	0
6/25/96	2.34	0.000	0.051	0
.	.	.	.	.
.	.	.	.	.
8/12/96	1.78	0.000	0.069	0
8/13/96	3	0.000	0.541	0.269
8/28/96	2.62	0.000	0.815	0.553
10/27/96	7.9	0.000	6.17	6.32
11/8/96	3.51	0.000	1.306	1.298
Total	139.6	41.522	60.369	48.456
tTest			0.226	0.768

Measured and DRAINMOD-ORIGINAL and DRAINMOD-Ks-STMAX models predicted runoff for the period between– 11/22/1996 to 11/22/1997 (Only days with runoff were included)

Date	Rain (cm)	M RO (cm)	DRAINMOD-O RO (cm)	DRAINMOD-K_s-STMAX RO(cm)
11/25/96	2.59	0.000	0.553	0
12/20/96	3.25	0.000	0.189	0
12/31/96	0	0.004	0	0
1/7/97	3.51	0.000	0.286	0
1/24/97	1.65	0.000	0.002	0
1/28/97	3.53	0.000	0.025	0
2/12/97	5.94	0.000	2.008	1.57
2/13/97	0.05	0.000	0	0.004
2/24/97	5.56	0.000	1.223	0.855
2/25/97	2.59	0.000	1.202	1.16
3/13/97	2.95	0.000	0.049	0
4/5/97	4.55	0.000	1.348	0.407
4/26/97	5.49	1.668	1.33	0.267
4/27/97	6.63	7.505	4.453	4.694
4/28/97	0.03	0.051	0	0
5/3/97	2.39	0.844	0.186	0
5/15/97	2.24	0.062	0	0
5/21/97	2.29	0.526	0	0
5/22/97	4.39	4.953	1.691	1.104
5/23/97	0.43	0.080	0	0
5/24/97	3.4	4.532	0.498	0.489
5/25/97	0.18	0.264	0	0
5/28/97	1.55	0.388	0	0
5/29/97	0.15	0.011	0	0
5/31/97	2.29	2.667	0.502	0.073
6/6/97	5.41	1.290	3.506	2.986
6/9/97	0.03	0.025	0	0
6/17/97	12.19	8.011	5.179	4.461
6/18/97	6.93	0.000	5.25	5.705
6/19/97	0.79	0.135	0	0
6/26/97	3.76	2.229	1.599	1.201
6/28/97	1.3	0.120	0	0
7/29/97	2.62	0.000	0.296	0.027
7/31/97	5.11	0.507	1.948	1.655
8/7/97	3.35	0.021	0.771	0.511
8/8/97	1.9	0.392	0	0
8/20/97	5.21	3.169	2.505	2.191
8/21/97	0.05	0.019	0	0
8/31/97	1.9	0.000	0.133	0
9/6/97	1.98	0.000	0.133	0
10/24/97	5.87	0.007	2.153	1.576
11/12/97	6.4	2.479	1.989	1.973
11/21/97	3.94	4.174	1.29	1.276
11/22/97	0	0.003	0	0
Total		46.236	42.297	34.185
tTest			0.81	0.46

VITA

Daniel Moriasi was born in 1966 in Nyamira District, Kenya, to Esther and Erasto Moriasi. He obtained his Bachelor of Science degree in agricultural engineering from Egerton University, Kenya, in September 1992. He taught math and physics in high school at Kebabe Secondary School, Kenya. He joined the Department of Biological and Agricultural Engineering in Louisiana State University in June 1995 and obtained the degree of Master of Science in biological and agricultural engineering in December 1997. He worked as a research associate with USDA-ARS while working on his doctoral program in engineering science. In December 2002, he married the most beautiful woman in the world, Cate Munene. God willing, he expects his firstborn son, Michael, in November 2004. He plans to work in a research or academia related field.